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INCOMPRESSIBLE FLOW FRICTION COEFFICIENTS IN A SIMULATED HEAT PIPE

THESIS

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THESIS

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David A. Manley

Table of Contents

List of Figures

Notation

A	porous pipe property used in Equation 2-3 $\left(\frac{lb_f - ft}{sec}\right)$
A_c	pipe cross-sectional area (ft^2)
A_p	pipe wall perimeter area (ft^2)
D	pipe diameter (ft)
f	friction coefficient (Eq 3-3)
f^*	impermeable wall friction coefficient
$\bar{f}_c$	average condenser friction coefficient (Eq 3-16)
F_c	axial force acting on condenser (Eq 3-15)
g_c	conversion factor $\left[\frac{lb_m - ft}{lb_f - sec^2}\right]$
L	pipe length (ft)
M	Mach number
$\dot{m}$	mass flow rate $\left(\frac{lb_m}{sec}\right)$
P	pressure $\left[\frac{lb_f}{ft^2}\right]$
R	ideal gas constant for air $\left[\frac{lb_f - ft}{lb_m - {}^\circ R}\right]$
Re_w	radial Reynolds number (Eq 3-14)
Re_x	axial Reynolds number (Eq 3-13)
T	temperature (${}^\circ R$)
$\bar{U}$	average axial velocity (ft/sec)
V_w	radial velocity at wall (ft/sec)

X	axial location (ft)
$\Delta(P^2)$	difference in square of pressures across pipe wall $\left(\frac{lb_f^2}{ft^4}\right)$
ΔW	change in momentum (lb_f)
ΔX	axial increment (ft)
ϕ	momentum flux factor (Eq 1-1)
γ	ratio of specific heats
μ	dynamic viscosity $\left(\frac{lb_f - sec}{ft^2}\right)$
ν	momentum diffusivity (ft^2/sec)
ρ	density $\left(\frac{lb_m}{ft^3}\right)$
ρV_w	mass flux $\left(\frac{lb_f - sec}{ft^3}\right)$
τ_w	wall shear stress $\left(\frac{lb_f}{ft^2}\right)$
ξ	dimensionless axial velocity (Eq 2-1)

<u>Superscripts and Subscripts</u>:

CE	condenser entrance
D	end of the condenser
LE	end of the evaporator
U	beginning of the evaporator
1	upstream end of the ΔX increment
2	downstream end of the ΔX increment

Abstract

This thesis examines the combined effects of pressure gradients and blowing and suction on frictional forces in a heat pipe with relatively low radial Reynolds numbers. A porous tube is used to simulate the heat pipe and a vacuum pump is used to generate the air flow. By measuring the static pressure variation along the pipe wall and using a one-dimensional, incompressible, numerical model, the frictional forces are obtained and compared to laminar fully-developed theoretical values. Four flow rate cases with radial Reynolds numbers of 1.8, 3.5, 6.5, and 12.6 were studied. In this range, the flow in the evaporator was fully-developed. In the condenser, however, the fully-developed solution consistently under predicted the average condenser friction coefficient. Deviation from the fully-developed solution increased as the flow rate increased.

INCOMPRESSIBLE FLOW FRICTION COEFFICIENTS IN A SIMULATED HEAT PIPE

I. Introduction

The purpose of this chapter is twofold. First, a review of past efforts, both analytical and experimental, which studied flow conditions in porous constant diameter circular cylinders with mass transfer at the walls will be made. This review will provide a framework for understanding the results of this investigation in addition to providing sources for comparison. Second, the objective and scope of this study will be outlined.

Literature Review

Examining fluid flow in porous tubes has proven to be an excellent way of understanding the combined effects of pressure gradients and blowing and suction on frictional forces in heat pipes. Most investigators have concentrated on the effects of either blowing or suction separately. For this reason, the literature discussed will be separated into 1) laminar flow in a porous tube with blowing, 2) laminar flow in a porous tube with suction, and 3) flows simulating heat pipe operation.

Laminar Flow in a Porous Tube With Blowing. Berman (1) was the first to solve the Navier-Stokes equations for steady, fully-developed, incompressible, laminar flow in a porous tube with uniform injection. He observed that fluid injection through the pipe walls has a noticeable effect on velocity profiles and pressure gradients. He showed that blowing in all cases would cause the pressure to decrease in the direction of axial flow. He also found that blowing would flatten the velocity profile at the center of the pipe and increase the slope of the profile at the pipe wall.

Kinney (2) using a numerical solution to the boundary-layer equation, showed that for fully-developed laminar pipe flow with either uniform blowing or suction, the product of the friction coefficient, f, and axial Reynolds number, Re_x is only a function of the radial Reynolds number, Re_w. He termed this relationship "the universal law of wall friction." With no blowing nor suction, $f \cdot Re_x = 16$. He further noted that this product increases with blowing and decreases with suction. Kinney also discussed the importance of a parameter he termed "the momentum flux factor," which is defined as

$$\phi = \frac{\overline{U^2}}{(\bar{U})^2} \tag{1-1}$$

This parameter provides an indication of the relative flatness of the velocity profile. For the impossible case

of slug flow, ϕ would equal unity, while for the impermeable wall case in fully-developed laminar pipe flow, ϕ is equal to 1.33. For increasing blowing rates, which have flatter velocity profiles, ϕ decreases asymptotically to 1.2337. Finally, Kinney verified that "for a given axial Reynolds number, blowing increases the wall friction." This is opposite to that found for flat-plate boundary-layer flows for which the wall friction is reduced by fluid injection normal to the wall. The reason for this is that for boundary-layer flow over a flat-plate at zero incidence, the axial pressure gradient is zero, even in the presence of uniform blowing normal to the plate surface. Here, blowing decreases the slope of the velocity profile at the surface resulting in less wall friction. For the pipe flow with blowing, the axial pressure gradient is negative to provide the force required for axial acceleration. As the magnitude of the pressure gradient increases with blowing, the slope of the velocity profile near the wall increases. The end result is greater wall friction.

The first attempt to verify experimentally the similarity solutions for fully-developed laminar flow in a porous pipe with wall injection was performed by Bundy and Weissberg (3). They were able to confirm the negative axial pressure gradients predicted by Berman.

Gupta (4) studied the effect of blowing on the laminar flow in the inlet region of a tube. His interest was in

controlling the length of the inlet region. Because blowing increases boundary-layer growth, his proposal was to use blowing as the controlling device. His analysis assumed steady, laminar flow of an incompressible Newtonian fluid entering a circular tube with a constant uniform velocity. The same fluid was injected into the flow, normal to the wall at a constant velocity. He found that as the blowing Re_w increased, the axial distance required for the attainment of a fully-developed flow solution decreased. He also found that for a given blowing Re_w, the length required to achieve the fully-developed solution decreases as the inlet axial Reynolds number is decreased. This fact when applied to heat pipes, where the flow begins in the evaporator with no axial velocity, allows the hydrodynamic entrance length in the evaporator to be ignored for even extremely small evaporation rates.

Bowman (5), determined experimentally that transition is retarded due to mass injection. He found that the flow remains laminar, when blowing is present, up to axial Reynolds numbers on the order of 10^6. Combining Gupta's observation that, with blowing, fully-developed laminar flow is quickly achieved with Bowman's observation that, with blowing, the flow remains fully-developed and laminar provides an insight as to why flow with blowing is relatively well behaved compared to flow with suction.

Laminar Flow in a Porous Tube With Suction. Berman (1) showed that, for fully-developed laminar flow, relatively small amounts of suction can lead to a pressure rise in the axial flow direction. In the presence of suction at the wall, the decrease in axial momentum tends to cause an increase in pressure in the flow direction, while the wall shear tends to decrease the pressure. He demonstrated that changes in the familiar parabolic velocity profile observed in tubes with impermeable walls are much more pronounced when fluid is removed through the system boundary than when fluid is injected. For small suction, the centerline value of the velocity increases and the slope of the profile at the wall decreases. Because the velocity of the fluid near the wall is small, it is affected more by the adverse pressure gradient. As suction increases, the velocity gradient at the wall approaches zero resulting in a typical separation profile. He also noted that the amount of suction required to produce a separation profile is very small, (on the order of $Re_w = 4$). Moreover, he showed that this phenomena is independent of Re_x. In contrast, for external flows, where the pressure gradient is not dependent on the suction rate, suction actually stabilizes the flow.

In this region of instability Berman (1) made his most interesting discoveries. He noticed several peculiarities with his numerical similar solutions. First when $4.1 < Re_w < 4.6$, there are two similar solutions for the ratio of

maximum to average axial velocity, (similar in the sense that the shapes of the velocity profiles do not vary with distance along the pipe). He felt only one of the solutions had any physical significance and that transition to turbulent flow would occur before the second solution could ever be achieved. More importantly, when he sought similar solutions for Re_w between the range of 4.6 and about 18, he found that *none* existed. For Re_w greater than 18, he found additional multiple solution ranges corresponding to reverse flow in various regions of the flow between the wall and the centerline of the pipe. Berman did not expect the absence of solutions for Re_w between 4.6 and 18.

Weissberg (6) was the first to investigate the suction region identified by Berman as having a non-similar solution. It was Weissberg who first referred to this region as the "forbidden" range of suction rates. He dealt with the partial differential equation of motion for the pipe case when similarity of the solutions is not imposed. His main assumptions were steady, incompressible, axially-symmetric flow in a pipe with uniform suction. He simplified the general equation of motion for the limit of high axial Reynolds number. He concluded that the nonexistence of similar solutions is to be associated with a state of the flow field for which the entrance region extends all the way from the pipe inlet to the location where the axial velocity is reduced to zero by wall suction.

Weissberg's analysis narrowed this region to $4.8188 < Re_w < 15.2688$.

Kinney (2) also found that, for suction of a fully-developed laminar flow, wall friction decreases with increasing Re_w. He established the limit for Re_w which would cause the wall friction to be reduced to zero at no less than 4.626. The last calculation he carried out was for $Re_w = 4.618$. This can be compared to Berman's original estimate of 4.6.

Kinney also provided values for the fully-developed laminar ϕ when suction is present. He did not compute any ϕ's for $Re_w > 4.618$. For radial Reynolds numbers larger than this, fully-developed laminar flow does not exist. As suction increases from zero to the edge of the "forbidden" suction range, he showed ϕ for fully-developed laminar flow increasing from 1.33 to approximately 1.9.

Raithby (7), using the same assumptions as Berman and Kinney, determined the range for which the wall friction becomes zero in fully-developed laminar flow to be between Re_w of 4.5978 and 4.5980. Raithby, like Berman, had multiple solutions for suction radial Reynolds numbers greater than the "forbidden" suction range. He felt that the velocity profile selected by the flow would depend on the inlet velocity profile. The most probable profile would likely transition to turbulent flow due to a combination of

velocity profile inflections and an opposing pressure gradient.

Hornbeck, Rouleau, and Osterle (8) developed a numerical model to examine the entrance region for a round pipe with any entrance velocity profile and any suction boundary condition including inertia effects. They limited their analysis to cases where the suction rates were small, (small values for the ratio of the mean suction velocity to the mean axial velocity). As in the previous uniform suction studies, they found that for moderate suction rates, the loss of axial momentum flux resulting from flow through the wall was only partially offset by the wall shear and the pressure rose in the axial direction. For very small suction rates, radial Reynolds numbers of approximately 2 and less, the effect of wall shear will be greater than that due to the loss of axial momentum flux, and the pressure will drop with axial distance. For uniform inlet velocities, they found that the pressure would decrease axially even more than with a fully-developed laminar parabolic inlet velocity profile. For the uniform inlet velocity profile case, if Re_w is sufficiently large, the pressure would first decrease for some axial distance and then begin to rise. Only when the high velocity gradient at the wall has decreased enough, does the loss of axial momentum by flow through the walls begin to have its effect on the pressure, causing it to rise.

The first to experiment in the "forbidden" range of suction were Quaile and Levy (9). They also performed an analysis assuming steady, laminar, incompressible flow in a constant diameter porous tube with uniform suction at the wall to compare with their experimental results. They measured the axial pressure variations and the velocity profiles of a silicone fluid entering a region of uniform suction with a parabolic velocity profile. For these conditions, their results were compatible with the earlier theories. Provided in their report is a figure showing theoretical axial locations where separation should occur for a given Re_w. For Re_w between 6 and 22, the measured separation locations occurred slightly later than predicted. For $Re_w = 30$, the measured separation location occurred slightly earlier than predicted.

Flows Simulating Heat Pipe Operation. Measurement of vapor dynamics in actual heat pipes presents many experimental difficulties. Because heat pipes are carefully sealed from their environment, it is difficult to determine the velocity profiles in the vapor region. Wageman and Guevara (10) were able to demonstrate that injecting a fluid through the walls over half the length of a porous pipe and then extracting the fluid through the walls over the second half of the porous pipe simulated the vapor dynamics in a heat pipe quite well. The mass injection at the wall simulates the evaporator and the mass extraction at the wall

simulates the condenser. For heat pipes, the velocity profile leaving the evaporator is somewhere between the parabolic and uniform velocity profiles and unless the adiabatic region is sufficiently long, the parabolic profile is never attained at the inlet of the condenser. Since Wageman and Guevara, other researchers such as Quaile and Levy, and Bowman have used a porous pipe to simulate a heat pipe.

Kinney (2) as mentioned previously, developed a relationship for the friction coefficient and axial Reynolds number product for various radial Reynolds numbers for fully-developed laminar flow. Bowman (5) modified this incompressible relationship, based on experimental data, to extend to compressible flow. For laminar flow, he found the relationship to be

$$f \cdot Re_x = 16\left[1.2337 - 0.2337e^{\left(0.0363Re_w\right)}\right]e^{\left(\frac{6M^2}{5}\right)} \tag{1-2}$$

For turbulent flow with axial Reynolds numbers less than 150,000 Kinney and Sparrow (11) suggested the following relationship

$$f = f^*\left[1 + 17.5Re_x^{0.25}\left(\frac{V_w}{\bar{U}}\right)\right] \tag{1-3}$$

where V_w is the radial velocity at the wall, $\bar{U}$ is the average axial velocity, and f^*, the impermeable wall friction coefficient, may be estimated by the Blasius equation

$$f^* = \frac{0.079}{Re_x^{0.25}} \tag{1-4}$$

<u>Objective and Scope</u>

The primary objective of this research is to study the behavior of a simulated heat pipe operating at relatively low radial Reynolds numbers. To better understand this behavior, data from a simulated heat pipe will be processed with a one-dimensional, numerical model. To lower the radial Reynolds number via a lower density, air will be pulled through the porous tube with a vacuum pump instead of using compressed air upstream. The static pressure will be measured along the pipe wall. This pressure distribution becomes the input to a one-dimensional, incompressible, numerical model for a constant diameter porous tube with variable mass injection and extraction. The numerical model will provide the friction coefficient distribution in the evaporator as well as an average friction factor for the condenser. These friction coefficients will then be compared to the fully-developed solutions predicted by Kinney. Also, the measured axial separation locations will be compared to those predicted by Quaile and Levy.

II. Experimental Model

The purpose of this study was to obtain static pressure data (axial pressure distribution) for flow inside a porous tube simulating a heat pipe at relatively low radial Reynolds numbers. The pressure measurements were used as input to a one-dimensional numerical model discussed in detail in Chapter 3. In this chapter, a description of the porous pipe, a discussion of the experimental set up, and the calibration results will be presented.

Porous Pipe

Following the example of Bowman (5), an ultra high molecular weight polyethylene porous pipe was obtained from Porex Technologies, (PVC tube part # 5139). The pipe had an inside diameter of 0.5 inches and a wall thickness of 0.25 inches. The average pore size was 20 microns. The length used in the heat pipe simulation was 31.81 inches. The evaporator and condenser sections were both 15.66 inches long separated by an adiabatic, impermeable wall of 0.50 inches in length. Both ends were sealed with plastic caps to insure that all flow entering or leaving the pipe was through the pipe walls. Half of the pipe was then placed into a vacuum tank, with the opposite half exposed to ambient air (see Figure 2-1). A portable shop vacuum pump connected to the vacuum tank generated the flow.

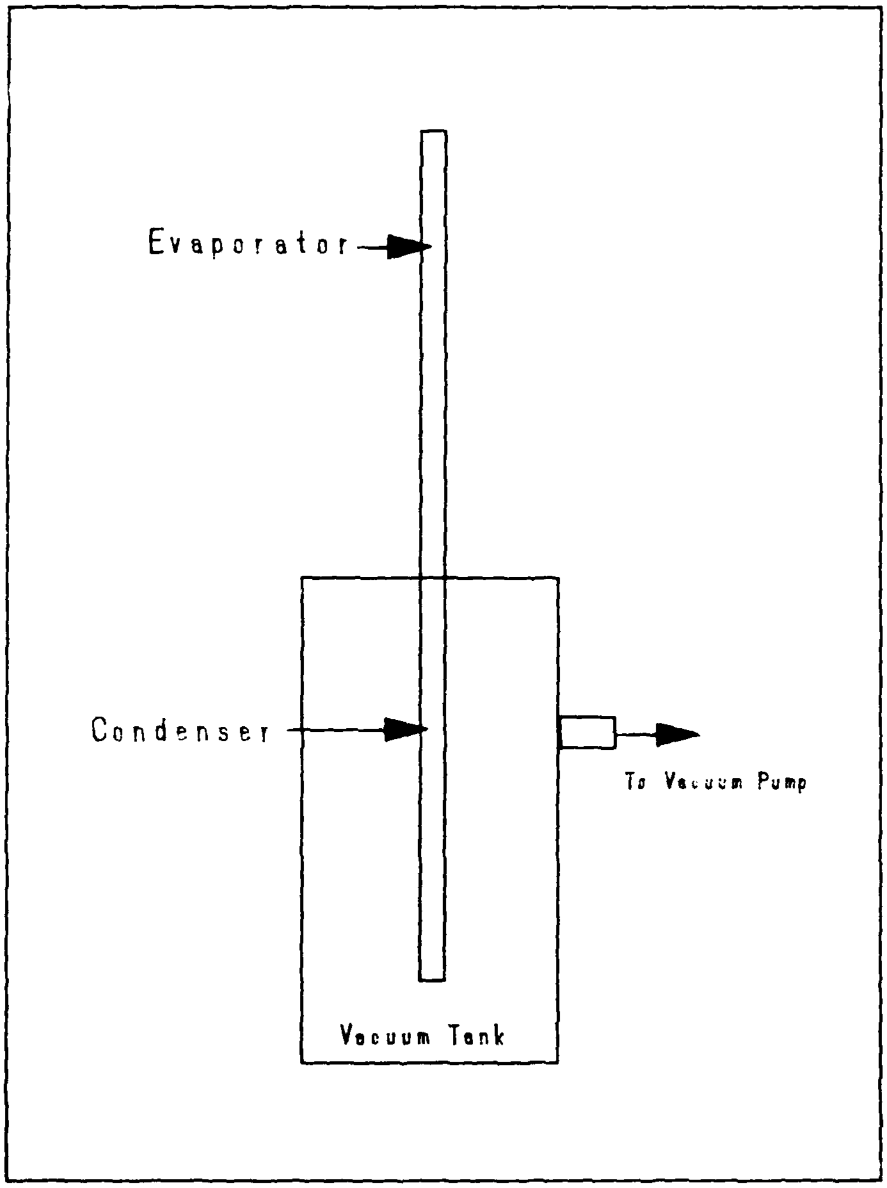

Figure 2-1. Experimental Test Configuration

Pressure Taps

Thirty pressure taps were installed in the porous pipe by cementing 0.5 inch long 0.060 inch outside diameter stainless steel tubes into 0.058 inch outside diameter holes drilled in the tube. This produced a snug fit. The stainless steel tube was inserted in the porous pipe so that its end was flush with the inside wall of the pipe. Two of the thirty pressure taps were installed through the end caps to obtain pressure measurements for ξ = 0.0 and ξ = 1.0 where ξ, the dimensionless axial location, is defined as

$$\xi = \frac{X}{L} \qquad (2\text{-}1)$$

The remaining twenty eight pressure taps were distributed axially along the pipe, eleven in the evaporator and seventeen in the condenser (see Figure 2-2), with their axial locations documented in the numerical code found in Appendix B.

Pressure Measurements

All pressure measurements were made using a T-type Scanivalve, from Scanivalve Corporation. A Robinson Halpern model 157B-W020D-F-V31 differential pressure transducer with a pressure range of +/- 0-2 inches of water producing an output of +/- 1 volt was used in the Scanivalve. The system allowed for 36 pressure measurements with the one pressure transducer. Two of the six remaining scanivalve ports were

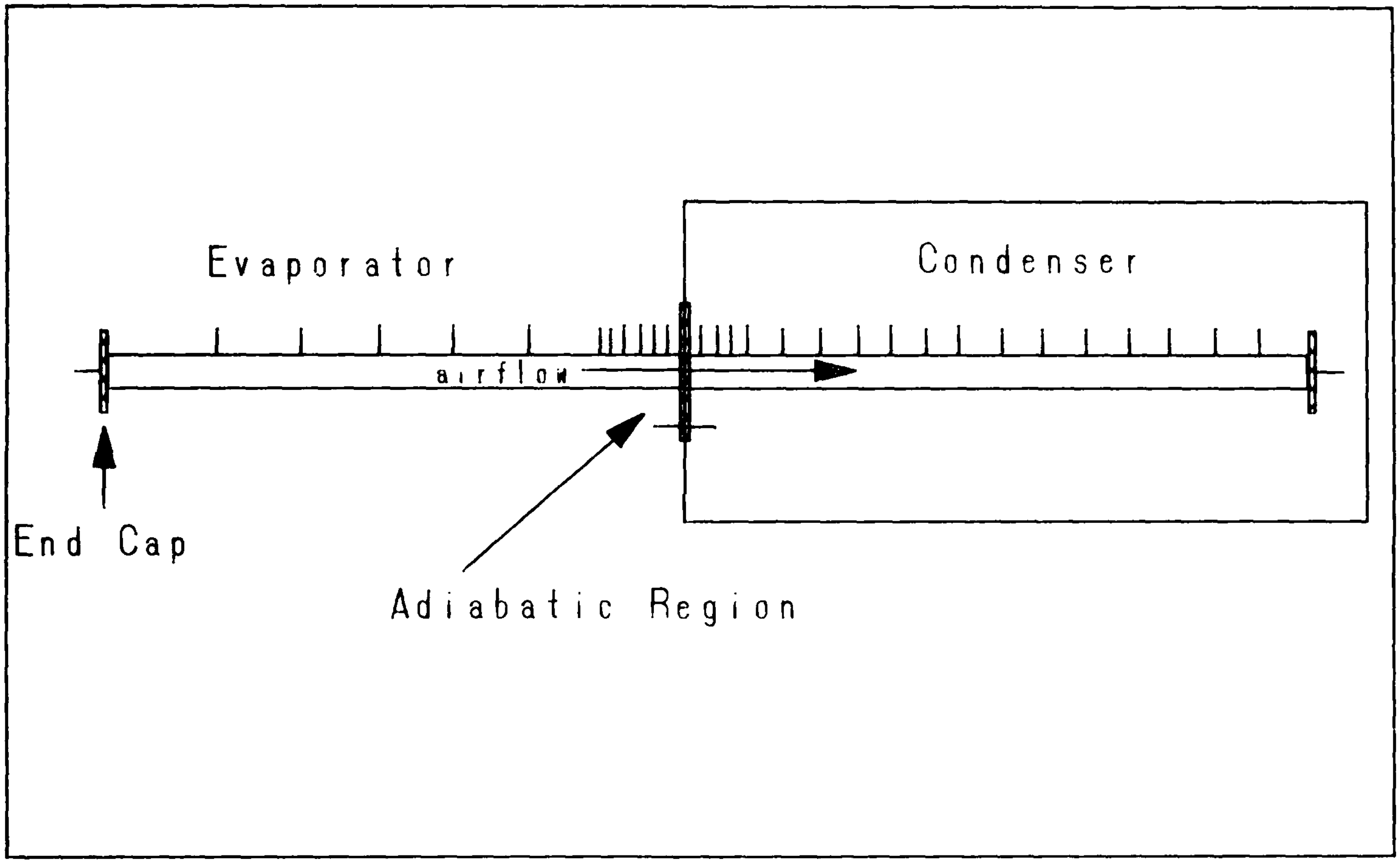

Figure 2-2. Pressure Tap Distribution

used to measure the pressure in the vacuum tank and the ambient pressure. For the three lowest flow rate cases, all pressure differences were measured with respect to ambient pressure. For the highest flow rate case, all pressure differences were measured with respect to the pressure port immediately leaving the evaporator. To obtain absolute pressures, the ambient pressure was measured with a barometer. The main disadvantage of the system was the amount of time required by the transducer's diaphragm to reach a steady pressure reading. The pressure transducer was calibrated using an inclined water manometer as the standard.

Data Acquisition

Data acquisition was done via a Zenith Z-100 computer. Pressure transducer input into the computer was digitized through a Dual Systems Control model AIM12 analog-to-digital card in the computer. An offset option on the transducer and the card's amplification were set so signals from 0 to +/- 1 volts could be read with a resolution of 0.04883 millivolts. Shielded cables were used to reduce noise introduced into the system. Noise was further reduced by averaging 1000 data samples for every pressure reading. To allow time for the transducer's diaphragm to reach equilibrium, a delay loop was used as the scanivalve changed ports. Once the data had been read and averaged by the

computer, it was displayed on the monitor and stored on an electronic disk.

Pipe Calibration

In addition to the pressure distribution along the porous pipe, the numerical model required information regarding the resistance of the porous pipe to mass flux (ρV_w) through its walls. Muskat (12) showed using Darcy's Law that, for the flow of a compressible gas through a porous medium, ρV_w can be related to the pressure difference across the porous medium by the expression

$$\Delta(P^2) = A(\rho V_w)^2 + B(\rho V_w) \qquad (2-2)$$

where the constants A and B are properties of the medium. For all cases of this study, the mass flux rates were very small and the contribution of the $A(\rho V_w)^2$ term was negligible. Muskat's relationship was therefore simplified to

$$\Delta(P^2) = B(\rho V_w) \qquad (2-3)$$

To determine the constant B, $\Delta(P^2)$ and ρV_w were measured at various mass flow rates. The two 2 inch samples used during the calibration were obtained from opposite ends of the porous pipe used to simulate the heat pipe. Two pressure ports for each sample connected to a 50 inch U-tube water manometer were used to measure the average pressure difference across the sample walls. A 1 inch precision bore

"flowrator" with a range of 0.05 - 0.44 cfm was used to measure ρV_w. The method used to measure $\Delta(P^2)$ and ρV_w was the same as outlined by Bowman (5) with the exception that flow was induced by a vacuum pump instead of compressed air. It was assumed that the temperature of the air entering the "flowrator" was the same as ambient. Using a least-squares technique to curve fit the experimental data shown in Figure 2-3, the constant B in Equation (2-2) was found to be $3.592472958 \times 10^{8} \frac{lbf}{ft\text{-}sec}$. As can be seen in Figure 2-3, the bob indicator tended to stick to the walls of the "flowrator" at the lower flow rates. When calibrating sample 1, readings were taken from the lowest to highest flow rates. When calibrating sample 2, readings were reversed.

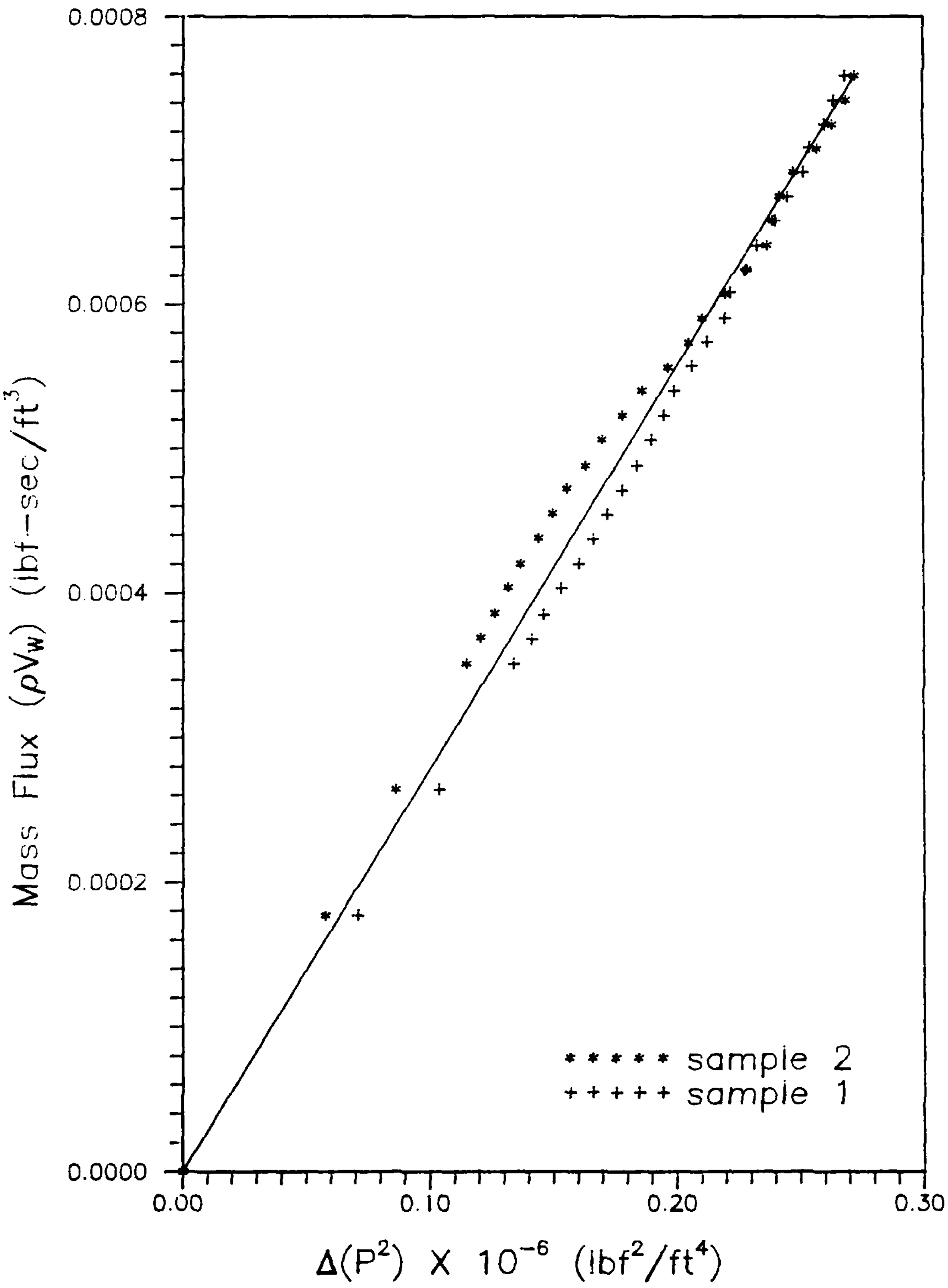

Figure 2–3. Porous Pipe Calibration Results.

III. Numerical Model

This chapter describes the one-dimensional numerical model used to reduce the data measured during the experimental phase of the study. First, the governing equations used in solving the flow properties will be presented. Then, the solution technique will be described.

Governing Equations

One-dimensional, steady, adiabatic, incompressible flow was assumed for the model. In the numerical simulation code contained in Appendix B, a provision for compressible flow has been made following the example of Holladay (13). All flows evaluated in this study, however, are incompressible.

To approximate the shear stress at the pipe wall, Newton's second law was applied to an element of fluid in the pipe as shown in Figure 3-1.

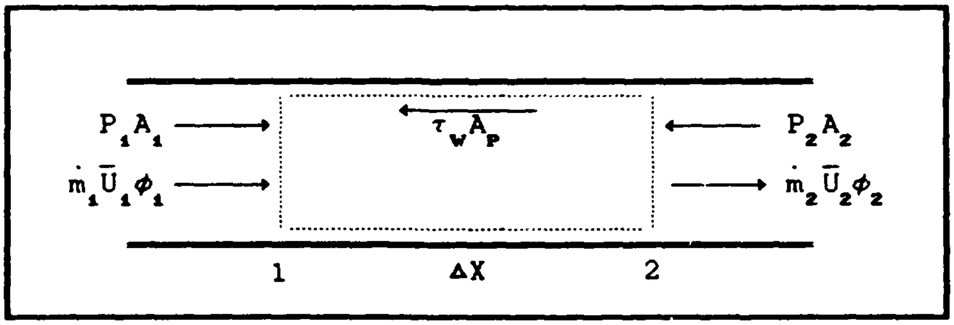

Figure 3-1. Element of Fluid for Equation of Motion

Applying Newton's second law for steady flow to the fluid element gives

$$\frac{\dot{m}_2 \bar{U}_2 \phi_2}{g_c} - \frac{\dot{m}_1 \bar{U}_1 \phi_1}{g_c} = \left(P_1 A_1 - P_2 A_2\right) - \tau_w A_p \qquad (3\text{-}1)$$

where A_p is the wall surface area for the increment ΔX. Solving for τ_w gives

$$\tau_w = \frac{1}{A_p} \left[\frac{\dot{m}_1 \bar{U}_1 \phi_1}{g_c} - \frac{\dot{m}_2 \bar{U}_2 \phi_2}{g_c} + \left(P_1 - P_2\right) A_C \right] \qquad (3\text{-}2)$$

where A_C is the cross-sectional area equal to A_1 and A_2. The friction coefficient is given by

$$f = \frac{2\tau_w g_c}{\rho \bar{U}^2} \qquad (3\text{-}3)$$

where

$$\bar{U} = \frac{\left(\bar{U}_1 + \bar{U}_2\right)}{2} \qquad (3\text{-}4)$$

Substituting the expression for τ_w given by Equation (3-2) in Equation (3-3) gives an expression for the friction coefficient in terms of quantities which can be calculated from the input pressure distribution

$$f = \frac{2\left[\Delta W + \left(P_1 - P_2\right) A_C\right] g_c}{\rho \bar{U}^2 A_p} \qquad (3\text{-}5)$$

where

$$\Delta W = \frac{\dot{m}_1 \bar{U}_1 \phi_1}{g_c} - \frac{\dot{m}_2 \bar{U}_2 \phi_2}{g_c} \tag{3-6}$$

The average axial velocities along the pipe were calculated from a mass balance on an element of fluid in the pipe as seen in Figure 3-2.

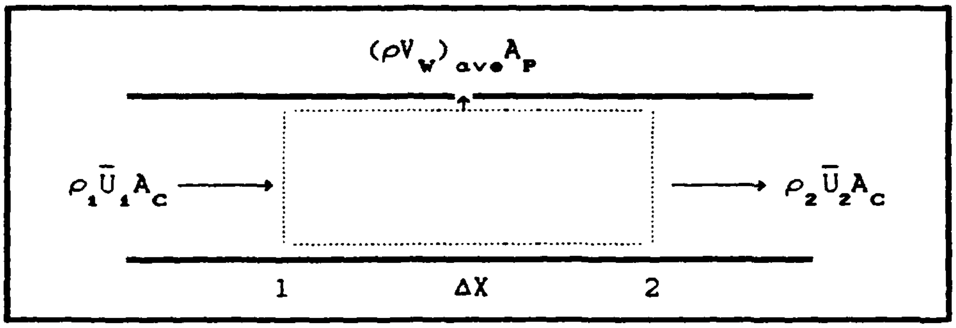

Figure 3-2. Element of Fluid Used For Mass Balance

Performing a mass balance on the fluid element in Figure 3-2

$$\rho_2 \bar{U}_2 A_C = \rho_1 \bar{U}_1 A_C - (\rho V_W)_{ave} A_P \tag{3-7}$$

where $(\rho V_W)_{ave}$ is the average mass flux through the pipe walls over the increment ΔX found by applying Equation (2-2) at stations 1 and 2 (shown in Figure 3-2) and taking the average of the two. The quantity $(\rho V_W)_{ave}$ is considered negative for blowing, and is considered positive for suction. Equation (3-7) can be solved for $\bar{U}_2$ giving

$$\bar{U}_2 = \frac{\rho_1 \bar{U}_1}{\rho_2} - \frac{(\rho V_W)_{ave} A_P}{\rho_2 A_C} \tag{3-8}$$

The velocity $\bar{U}_1$ is taken from the previous step and is initially zero.

The pressure at each step was found by interpolating from the input pressure distribution using the second degree interpolation formula outlined by Holladay (13). The temperature (T), viscosity (μ), axial Reynolds number, and radial Reynolds number were calculated from the following expressions:

$$T = \frac{T_o}{\left[1 + \frac{(\gamma - 1)M^2}{2}\right]} \quad ; \quad T = T_o \tag{3-11}$$

$$\mu = \frac{2.27E\text{-}08 \cdot (T)^{1.5}}{(T + 198.6)} \tag{3-12}$$

$$Re_x = \frac{4\dot{m}_{ave}}{\left[\pi D \mu g_c\right]} = \frac{\rho \bar{U} D}{\left[\mu g_c\right]} \tag{3-13}$$

$$Re_w = \frac{(\rho V_w)_{ave} D}{\left[\mu g_c\right]} \tag{3-14}$$

where $\dot{m}_{ave}$ is the average of $\dot{m}_1$ and $\dot{m}_2$.

Because ϕ in the evaporator was known and nearly constant, the total force for the condenser could be determined.

$$F_C = \left(P_U - P_D\right) A_C - \sum_{i=U}^{CE} \left(\tau_W A_P\right)_i \qquad (3\text{-}15)$$

where the subscripts U, D, and CE represent the beginning of the evaporator, the end of the condenser, and the condenser entrance, respectively. By using average condenser values for axial velocity and density, the average friction coefficient for the condenser could be evaluated using

$$\bar{f}_C = \frac{F_C}{\left(\frac{\rho_C \bar{U}_C^2}{2g_c}\right) A_C} \qquad (3\text{-}16)$$

The average condenser axial velocity was calculated as half the axial velocity entering the condenser.

Solution Method

A marching technique was used to solve for flow properties along the simulated heat pipe. The static pressure data obtained from the experimental work was first read into the computer code. Next, the program prompted for average values of ϕ for the blowing and suction regions. With predefined constants for the pipe geometry and air properties available, and knowing the initial conditions at

$\xi = 0.0$, the set of governing equations were used to solve for the downstream Mach number, axial Reynolds number, radial Reynolds number, and friction coefficient for each ΔX increment along the pipe.

Three subroutines were utilized to 1) interpolate for intermediate pressures, and solve for flow properties for either 2) incompressible, or 3) compressible flow. These subroutines were individually verified using known input and output values. The main program was verified by using the pure mass case (no friction). Using Shapiro's influence coefficients for pure mass addition (14), with constant specific heat and molecular weight

$$\dot{m} = \dot{m}^* \frac{M\sqrt{2\left(\gamma+1\right)\left(1+\frac{\gamma-1}{2}M^2\right)}}{1+\gamma M^2} \tag{3-17}$$

and

$$P = P^* \frac{\gamma+1}{1+\gamma M^2} \tag{3-18}$$

and for a constant wall mass flux, $\dot{m}''$

$$\frac{d\dot{m}}{\dot{m}} = \frac{dx}{x} \tag{3-19}$$

the Mach number as a function of axial location, x, can be found using

$$x = \frac{x^{*} M \sqrt{2\left(\gamma+1\right)\left(1+\frac{\gamma-1}{2} M^{2}\right)}}{1+\gamma M^{2}} \tag{3-20}$$

Selecting the Mach number at the end of the evaporator, LE, determines x^{*} and specifies a Mach number for each axial location. The pressure variation is then known using

$$P = \frac{P_{o}}{1+\gamma M^{2}} \tag{3-21}$$

where P_o is the pressure at the end of the tube. Solving for the constant mass flux, $\dot{m}''$, gives

$$\dot{m}'' = \frac{\dot{m}_{LE}}{\pi D x_{LE}} \tag{3-22}$$

where

$$\dot{m}_{LE} = \left[\frac{PM\pi D^{2}}{4} \sqrt{\frac{g_{c}\gamma}{RT}}\right]_{LE} \tag{3-23}$$

The static pressure in the condenser for the pure mass case mirrors the evaporator solution.

For the experimental cases, the numerical code provided two additional checks. First, the force balance over the entire pipe was calculated. When considering the pipe system, the only forces acting on the fluid are the pressures at the ends of the pipe and the total wall shear force.

$$\text{Force Balance} = \left(P_U - P_D\right)A_C - \sum_{i=U}^{D}\left(\tau_W A_P\right)_i \qquad (3\text{-}24)$$

Ideally, the Force Balance should be zero since the drop in pressure between the two ends of the pipe is a result of the wall shear stress. A relative percent error was provided by dividing the Force Balance by the pressure force and multiplying by 100. The final check made was a mass balance over the entire pipe to see if the total mass injected into the pipe equaled the total mass removed from it. A relative percent error was provided by dividing the mass balance by the mass entering the condenser and multiplying by 100.

IV. Discussion of Results

As can be seen from Figure 4-1, Re_w for all four test cases was relatively constant. As the flow rates increased, the axial variation of Re_w became more obvious. The largest flow rate case had a 0.9 % change in Re_w between the beginning of the evaporator and the end of the condenser.

Figure 4-2 shows how the pressure varied axially along the walls of the simulated heat pipe for all four Re_w cases. The data used to create Figure 4-2 can be found in Appendix A. The pressure variation obtained along the pipe was a result of two effects: 1) the friction encountered along the pipe walls, and 2) the rate of change in momentum along the pipe. For flow without friction, the pressure would drop as the flow accelerated in the evaporator and would completely recover as the flow decelerated in the condenser. The total effect of the wall friction force can be seen as a pressure deficit at the end of the pipe. In each of the four Re_w cases, the flow did not achieve complete pressure recovery. The pressure drop due to friction was found to increase with increased mass flow rate. For the lowest flow rate case, (Re_w = 1.8), the pressure in the condenser dropped instead of rising. This occurred, as predicted by Hornbeck, et. al. for suction radial Reynolds numbers less than approximately 2 (8), because the effect of wall shear is greater than that due to the loss of axial momentum flux.

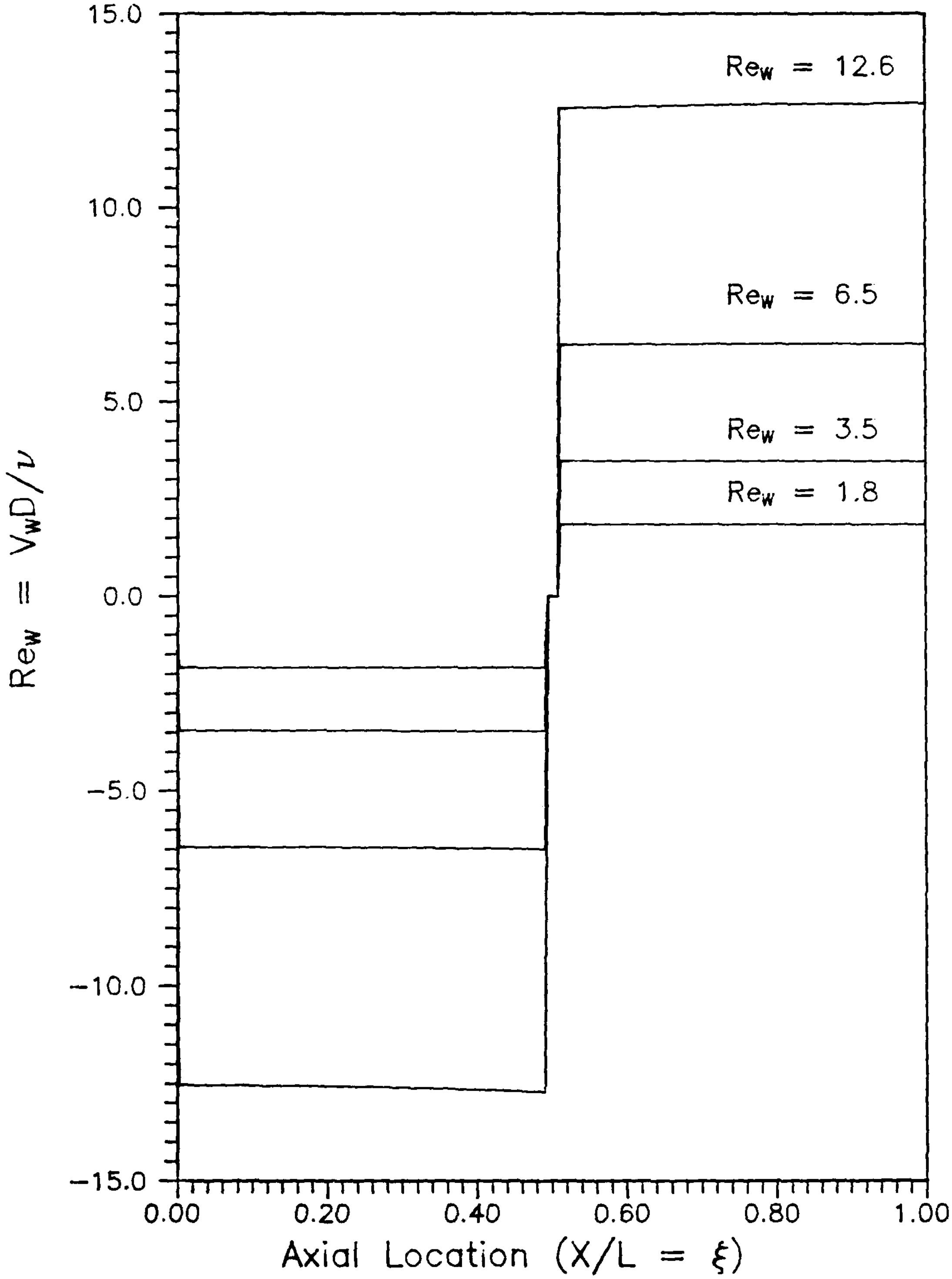

Figure 4–1. Experimental variation of radial Reynolds number with axial location along porous pipe.

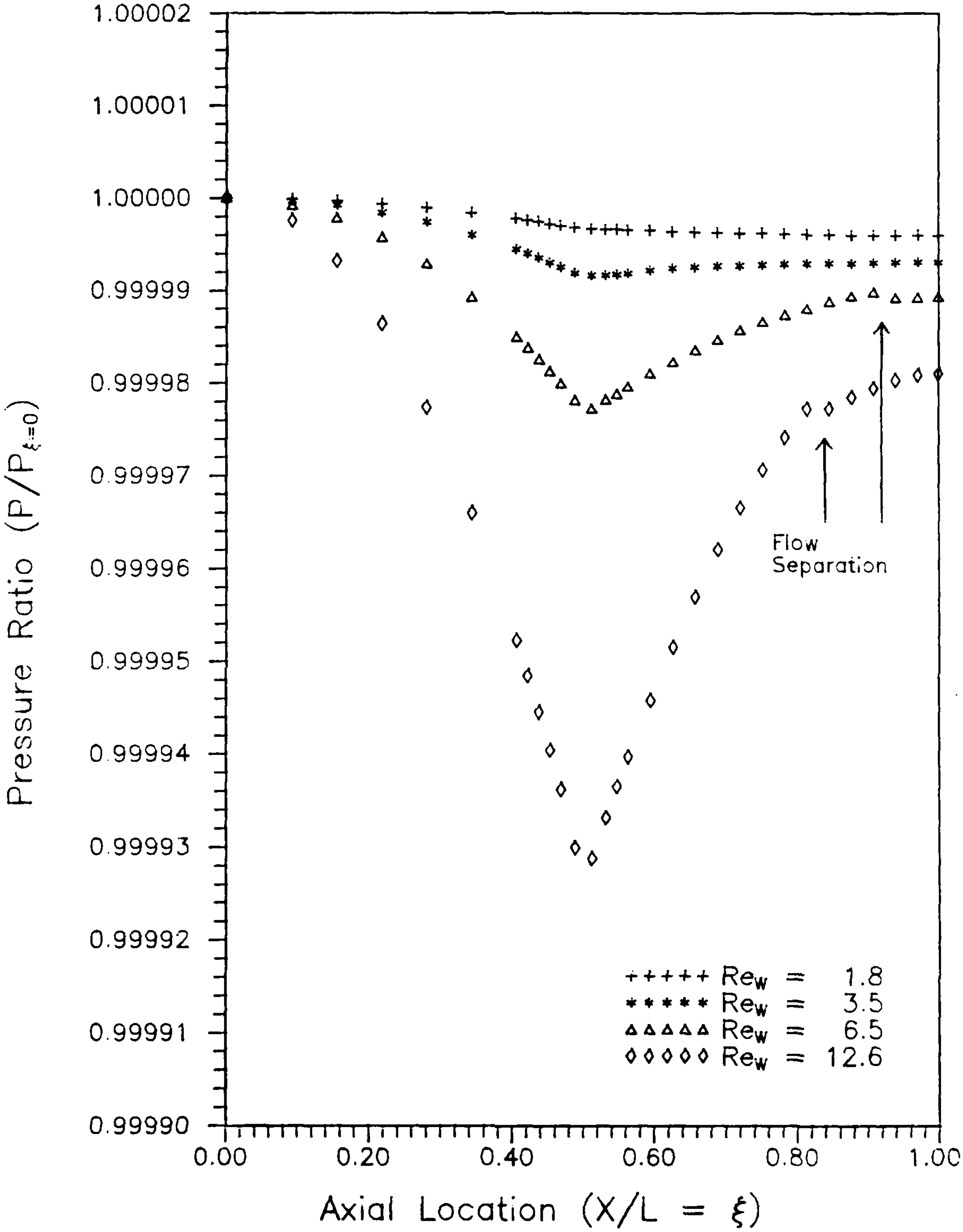

Figure 4–2. Experimental variation of wall static pressure with axial location along porous pipe.

As can be seen in Figure 4-2, flow separation occurred in the condenser for the Re_w of 6.5 and 12.6 cases. To compare separation locations with those predicted and measured by Quaile and Levy (9), their non-dimensional coordinate system had to be converted to that used in this experiment since they did not have an evaporator region preceding their suction region. Figure 4-3 has three pieces of information: 1) a curve fit of Quaile and Levy's converted theoretical separation predictions, 2) the converted experimental separation locations found by Quaile and Levy, and 3) the separation locations found in this experiment. Recall that Quaile and Levy assumed uniform suction and a parabolic inlet velocity in their derivation of theoretical separation locations. The suction in this experiment was nearly uniform as can be seen in Figure 4-1, however, since the flow entering the suction region was preceded by a blowing region and a short impermeable wall with an L/D of 1, the velocity profile entering the condenser will be flatter than parabolic, ($\phi < 1.33$). The velocity profile entering the suction region requires some axial distance to adjust to local wall conditions. This would explain why separation in this experiment occurred slightly after that predicted by Quaile and Levy. The two lowest flow rate cases had Re_w's less than 4.6, the approximate Re_w which would cause separation in a fully-developed flow. No flow separation occurred for these

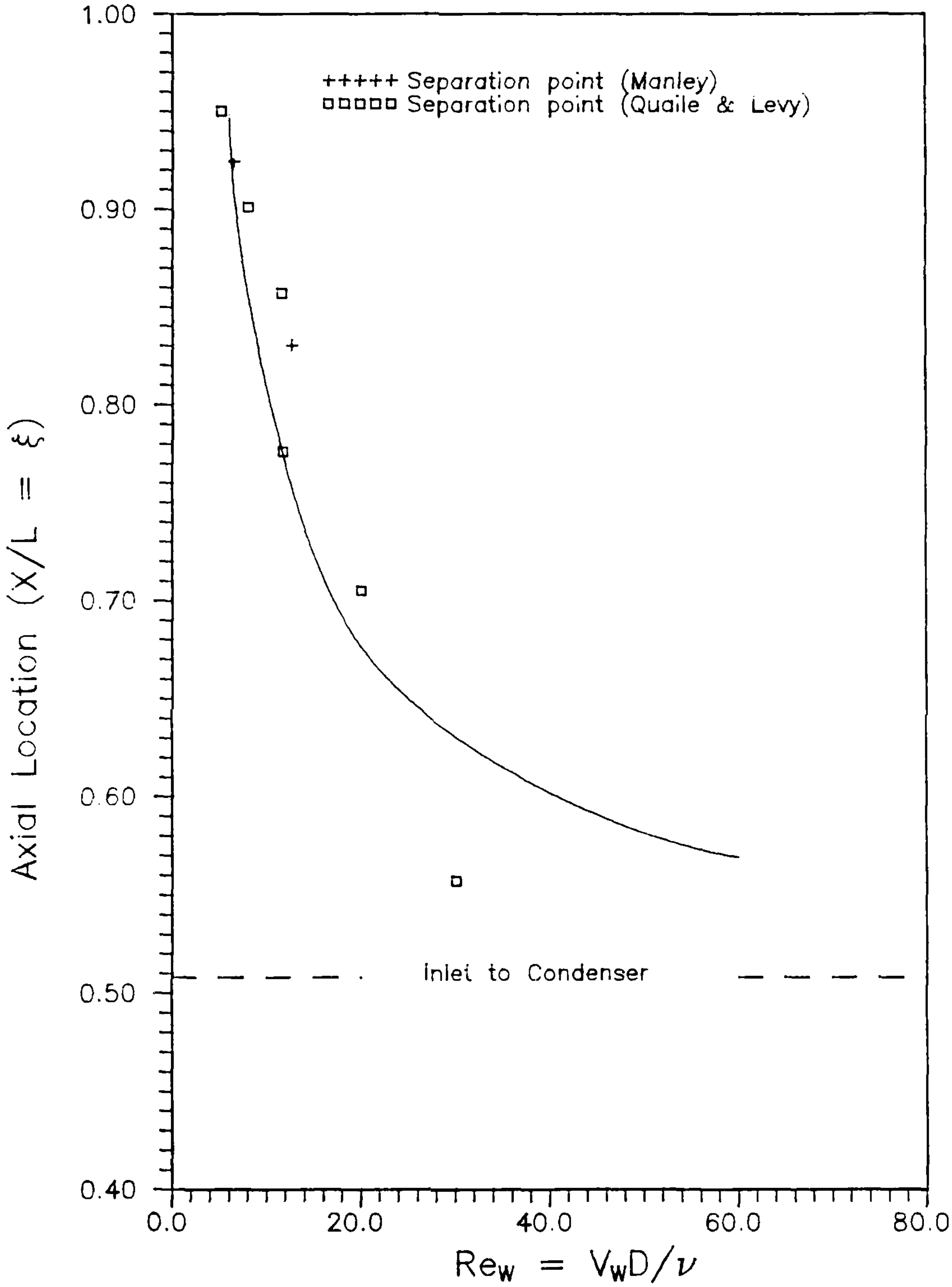

Figure 4–3. Curve Fit of Quaile and Levy's Prediction of Separation for constant wall suction and parabolic inlet velocity profile.

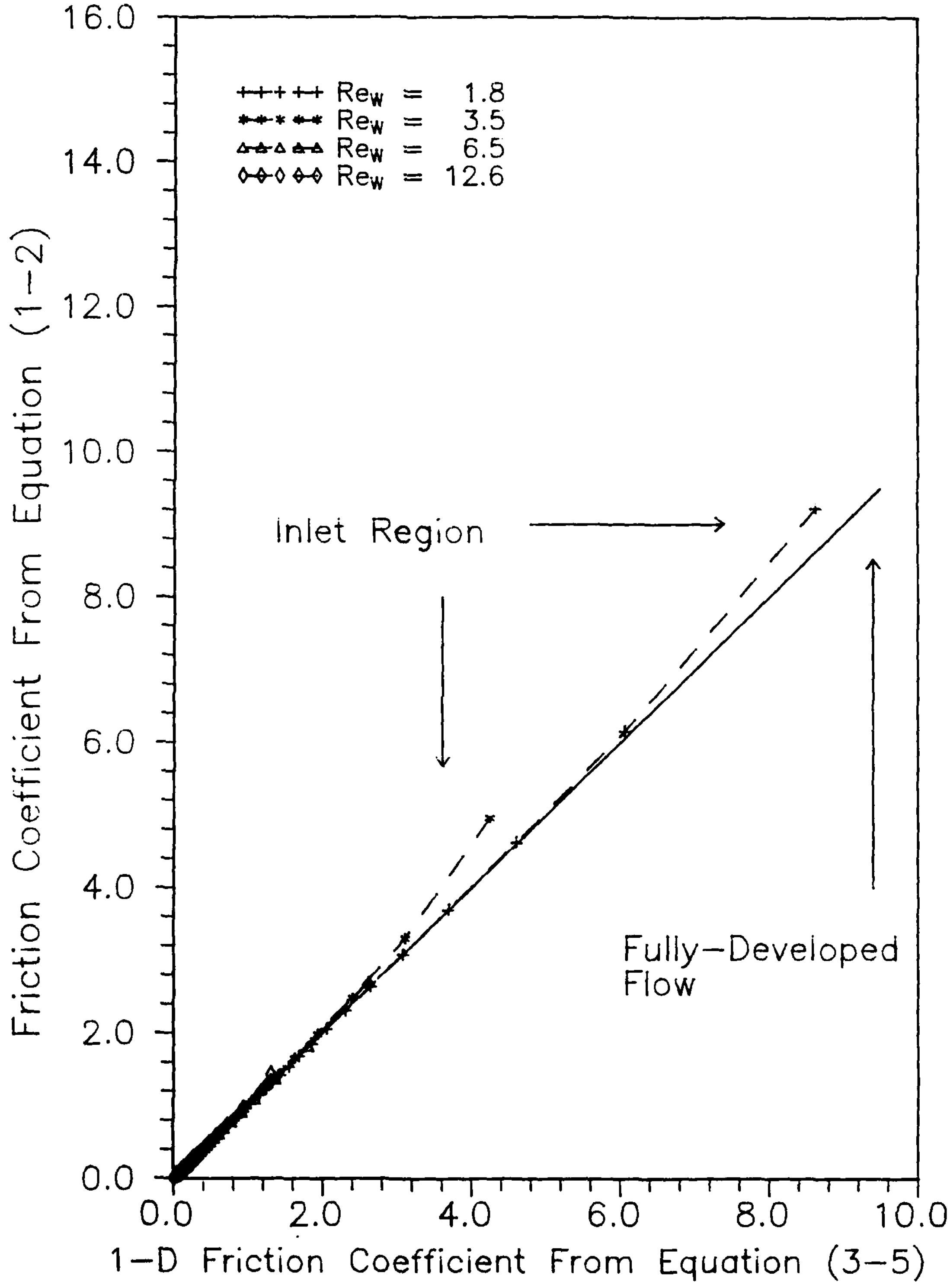

Figure 4-4. Evaporator (Blowing) Friction Coefficient Results.

cases. For the two cases where separation occurred, the axial location plotted in Figure 4-3 corresponds to the center of the two pressure ports detecting separation.

Figure 4-4 is a graph of the evaporator friction coefficients calculated comparing the expression for fully-developed laminar flow, Equation (1-2), with the one-dimensional expression, Equation (3-5). For all four cases, the flow was fully-developed within four ΔX increments along the pipe. It should be noted, that the values calculated using Equation (3-5) are highly dependent on ϕ. The values of ϕ used were obtained from a graph Kinney (2) produced numerically assuming fully-developed laminar flow with constant blowing Re_w's. Bowman's Equation (1-2) is an empirical curve-fit of Kinney's results. The values obtained from Equation (3-5) differ slightly from those predicted by Kinney. However, by choosing a more appropriate ϕ, Kinney's results can be obtained. The first data points for each Re_w case plotted correspond to the third increment of the numerical data reduction program. These four data points deviate the farthest from the line for fully-developed laminar flow when compared to respective Re_w data points

Figure 4-5 is a graph comparing Kinney's (2) theoretical universal law of wall friction for fully-developed laminar flow in porous tubes with uniform suction, with the average condenser friction coefficients,

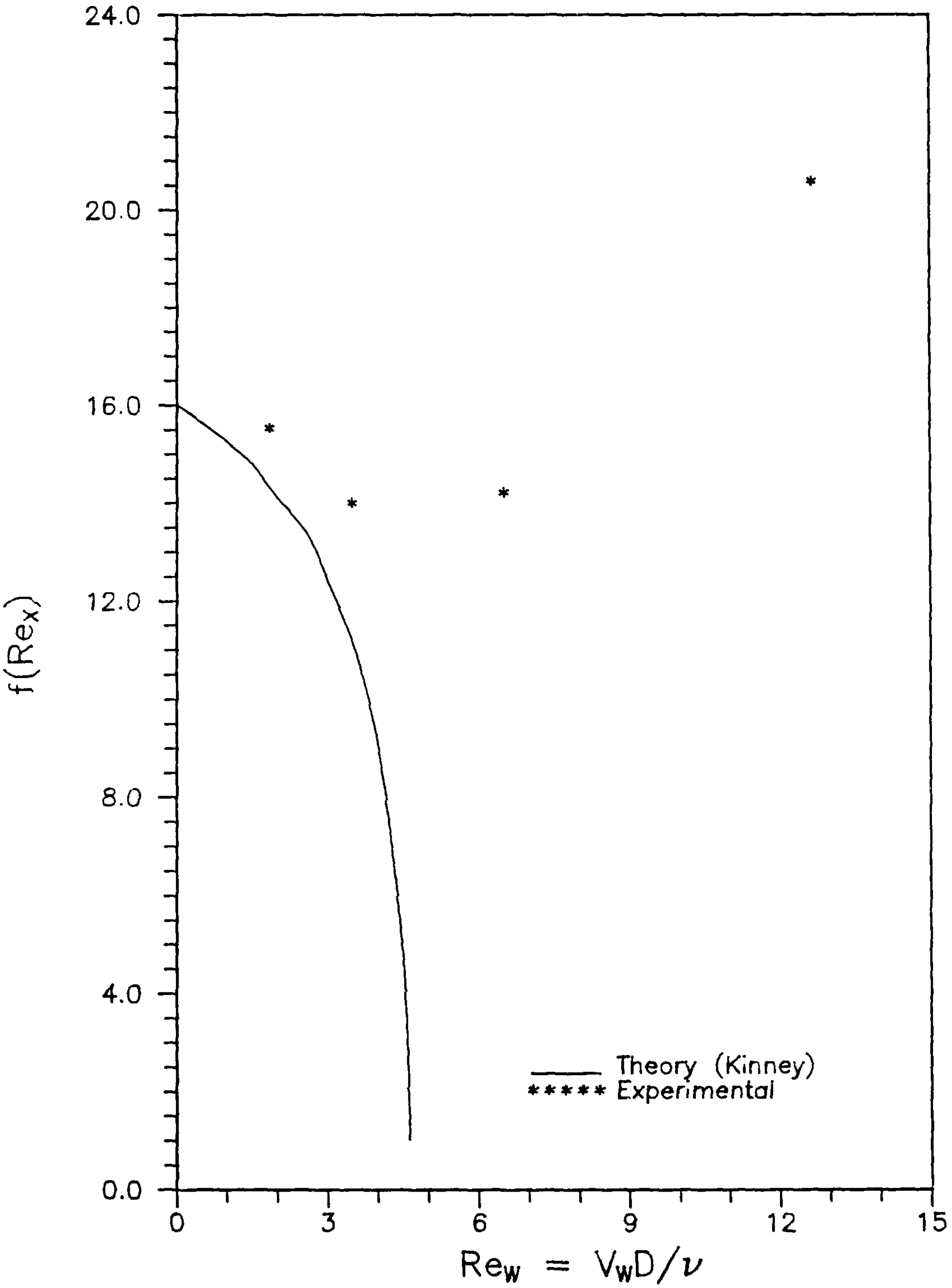

Figure 4–5 Curve fit of Kinney's universal law of wall friction for fully–developed laminar flow in porous tubes and average condenser values from this experiment.

$\bar{f}_c$, calculated using Equation (3-16). For the two lowest flow rate cases, $\bar{f}_c$ is slightly higher than that predicted by Kinney. This can be explained by the fact that the flow entering the condenser, due to the blowing in the evaporator, has a flatter velocity profile than the parabolic inlet velocity profile assumed by Kinney. During the length of the condenser where the flow is adjusting to a fully-developed flow, the friction should be higher than the fully-developed values. For the last two flow rate cases, higher friction due to the adjusting velocity profiles, in addition to separated flow would account for the larger deviations from Kinney's theoretical curve. The large friction coefficients after separation would more than balance the small friction coefficients in the regions preceding separation.

Appendix C contains printouts for the four flow rates. These printouts indicate the average values of ϕ used in the blowing and suction regions. They also show the relative percent errors for the force and mass balances encountered during the experimental and numerical data reduction phases. The maximum error was 0.0013 % in the force balance and 0.0312 % in the mass balance.

V. Conclusions and Recommendations

Conclusions

The results obtained from this investigation provide insights into the operation of heat pipes at relatively low radial Reynolds numbers. The fully-developed laminar flow solution can be used in the evaporator to obtain friction coefficients. In the condenser, however, the fully-developed solutions may not accurately predict wall friction. Above radial Reynolds numbers of 4.6, the hydrodynamic entrance regions can be a major portion of the condenser length. In heat pipes, unless there exists a sufficiently long adiabatic region, the flow entering the condenser has flatter velocity profiles than those in the impermeable wall case. Through the length of the condenser where the flow is adjusting to local wall conditions, the wall friction will be higher than the fully-developed solution. Also, because of this phenomenon, flow separation will be slightly delayed. In this investigation, an average condenser friction factor was found for radial Reynolds numbers less than 13. This result should prove helpful for design purposes.

Recommendations

Some ideas for further research are:

1) Experimentally determine condenser flow separation locations and average friction coefficients for radial

Reynolds numbers greater than 13, where blowing and suction rates are not constant, and the condenser inlet velocity profile becomes flatter.

2) Determine the onset of transition to turbulent flow and its effect on average condenser friction coefficients.

3) Perform a numerical, two-dimensional flow analysis, using experimental pressure data, to determine appropriate momentum flux factors, ϕ, for the developing flow in the condenser.

Appendix A: Experimental Data

This appendix contains raw data for the four flow rate cases obtained during the experimental portion of this study. Test run numbers 1, 2, 3, and 4 correspond to radial Reynolds numbers of 3.5, 1.8, 6.5, and 12.6 respectively. All pressures are given in psia and all temperatures are given in ^{o}R. The following format is used for all four test cases:

test run number
atmospheric pressure
ambient temperature
vacuum tank pressure
port 1 pressure, ξ = 0.0 (beginning of evaporator)
port 2 pressure
port 3 pressure
port 4 pressure
port 5 pressure
port 6 pressure
port 7 pressure
port 8 pressure
port 9 pressure
port 10 pressure
port 11 pressure
port 12 pressure, (last port in evaporator)
port 13 pressure, (first port in condenser)
port 14 pressure
port 15 pressure
port 16 pressure
port 17 pressure
port 18 pressure
port 19 pressure
port 20 pressure
port 21 pressure
port 22 pressure
port 23 pressure
port 24 pressure
port 25 pressure
port 26 pressure
port 27 pressure
port 28 pressure
port 29 pressure
port 30 pressure, ξ = 1.0 (end of condenser)

1
14.282667000000
526.50
14.244351480722
14.263613999968
14.263609987649
14.263602540310
14.263591359022
14.263576271017
14.263557421172
14.263534520094
14.263528299893
14.263521720020
14.263514807101
14.263507097221
14.263497110700
14.263497081109
14.263498061892
14.263499050988
14.263500745013
14.263504779938
14.263507824992
14.263509883195
14.263511303314
14.263512510296
14.263513600389
14.263514573218
14.263515434911
14.263516359503
14.263517049930
14.263517850391
14.263518084766
14.263518090997
14.263518091370

2
14.248416000000
526.00
14.228081934722
14.238297320471
14.238295723592
14.238292754917
14.238288259536
14.238282241124
14.238274679967
14.238265590919
14.238263080953
14.238260470171
14.238257765012
14.238254963998
14.238251650102
14.238250005044
14.238249248215
14.238248648028
14.238248065997
14.238246948099
14.238245915972
14.238244968116
14.238244105078
14.238243338026
14.238242661110
14.238242065994
14.238241548503
14.238241108511
14.238240752108
14.238240482496
14.238240294616
14.238240190500
14.238240163414

3
14.302239000000
526.00
14.230802744722
14.266756940340
14.266746082953
14.266726010212
14.266695605500
14.266654991066
14.266604022328
14.266542640400
14.266525647021
14.266508007998
14.266489624021
14.266470555221
14.266444511202
14.266431792928
14.266445921015
14.266455020220
14.266465723482
14.266485780049
14.266503172131
14.266521909861
14.266537951121
14.266552664012
14.266565232023
14.266576731019
14.266586102102
14.266597460074
14.266605711573
14.266611421120
14.266603292385
14.266604100374
14.266604363487

4
14.272881000000
526.00
14.133008654431
14.203597320072
14.203562960836
14.203499542432
14.203403802361
14.203275260128
14.203113651026
14.202918830572
14.202864878298
14.202808843901
14.202750764670
14.202690523947
14.202602026204
14.202584598832
14.202647510237
14.202695511205
14.202740492984
14.202826570110
14.202908462280
14.202985260293
14.203056868943
14.203121392452
14.203178934831
14.203229592391
14.203273830120
14.203274341038
14.203291310250
14.203305581193
14.203318130044
14.203325605621
14.203327728798

Appendix B


```
      PROGRAM ONED
C     TITLE:  ONE-DIMENSIONAL HEAT PIPE SIMULATION
C
C     BY: Captain David Manley
C         MS Thesis, 1988
C
C     This program uses one-dimensional incompressible
      and compressible
C     flow models to solve for the flow properties and
      friction
C     coefficients in a closed porous pipe with blowing
      and suction.
C     The incompressible model is used to calculate the
      flow properties
C     until the Mach number reaches 0.01.  Choosing 0.01
      was a purely
C     arbitrary decision.  For Mach numbers above 0.01,
      the compressible
C     model is used.  The compressible model utilizes
      Shapiro's method
C     of influence coefficients to solve for the flow
      properties.
C
C     ************************************
C     *****  DEFINITION OF VARIABLES *****
C     ************************************
C
C     A                   Constant obtained from pipe
                          calibration used in
C                         determining wall mass flux
                          (lbf/ft/sec)
C     AC                  Cross-sectional area of the pipe
                          (ft2)
C     AP                  Surface area of DX increment (ft2)
C     BETA                Ratio of radial Reynolds number to
C                         axial Reynolds number
C     CL                  Condenser Length (ft)
C     CC1                 Intermediate value used during
                          pressure
C                         interpolation subroutine  (CC2 and
                          CC3 are
C                         similar)
C     C2                  Speed of sound squared (ft2/sec2)
C     D                   Pipe inside diameter (ft)
C     DMOM                Change in momentum across DX
                          increment (lbf)
C     DPS                 (Pambient)**2 - (P2)**2
                          (lbf/ft2)**2
```

```
C     DX          Spacial step size (ft)
C     DW          Change in mass flow rate due to mass transfer at
C                 the wall (lbm/sec)
C     DWSUM       Summation of all the incremental mass flow rate
C                 changes over the entire pipe due to mass transfer
C                 at the wall (lbm/sec)
C     F           Friction factor
C     FBARC       Average condenser friction factor
C     FBL         Bowman's friction factor for fully-developed
C                 laminar flow
C     FBLREX      Product of FBL and axial Reynolds number
C     FBT         Kinney's friction factor for fully-developed
C                 turbulent flow
C     FBTREX      Product of FBT and axial Reynolds number
C     FCREXC      Product of FBARC and REXBRC
C     FSTAR       No blowing/suction fully-developed turbulent
C                 friction coefficient, (Blasius equation)
C     FUD         Constant to account for the statistical variation
C                 of the porous pipe calibration constant A
C     GAM         Ratio of specific heats
C     GC          Newton's gravitational constant (lbm-ft/lbf/sec2)
C     M1          Mach number at upstream end of DX increment
C     M2          Mach number at downstream end of DX increment
C     M1S         M1 squared
C     M2S         M2 squared
C     MFF         Momentum flux factor, (see Kinney pg 1398;IJHMT
C                 Vol 11 1968).  An indication of the velocity
C                 profile or shape
C     MFF1        Momentum flux factor at upstream end of DX
C                 increment
C     MFF2        Momentum flux factor at downstream end of DX
C                 increment
C     MFFB        Blowing momentum flux factor
C     MFFS        Suction momentum flux factor
```

```
C      MSBAR              Average of M1S and M2S
C      N                  Test Run number
C      PATM               Atmospheric pressure (entered in psia then
C                         converted to lbf/ft2)
C      PEF                Percent error for force balance
C      PEM                Percent error for mass balance
C      PF                 Pressure force on entire pipe due to the
C                         difference of pipe end pressures
C      PL                 Pipe length (ft)
C      PND(1)-PND(30)     Non-dimensional static pressure, P2/P(X=0.0)
C      P1                 Static pressure at upstream end of DX increment
C                         (lbf/ft2)
C      P2                 Static pressure at downstream end of DX increment
C                         (lbf/ft2)
C      P(1)-P(30)         Pressure measurements at corresponding axial
C                         positions, X(1)-X(29) (entered in psia and then
C                         converted to lbf/ft2)
C      R                  Ideal gas constant for air (lbf-ft/lbm/R)
C      REW                Radial Reynolds number based on pipe inside
C                         diameter
C      REX                Axial Reynolds number based on pipe inside
C                         diameter
C      REXBRC             Average axial Reynolds number for the condenser
C                         based on pipe inside diameter. REX entering
C                         condenser divided by 2
C      RHOC               Representative density of air for condenser
C                         (lbm/ft3)
C      RHO1               Density of air at beginning of DX increment
C                         (lbm/ft3)
C      RHO2               Density of air at end of DX increment (lbm/ft3)
C      RHOV1              Mass flux through the wall at the upstream end of
C                         the DX increment (lbm/ft2/sec)
C       RHOV2             Mass flux through the wall at the downstream end
C                         of the DX increment (lbm/ft2/sec)
C       RHOVAV            Average mass flux for DX
```

```
                                 increment (lbm/ft2/sec)
C      RHOBAR                   Average density of air for DX
                                 increment (lbm/ft3)
C      RMU                      Viscosity of air (lbf-sec/ft2)
C      SF                       Shear force over the increment DX
                                 (lbf)
C      SFC                      Shear force over the condenser
                                 (lbf)
C      SFEA                     Shear force over the evaporator
                                 and adaiabatic
C                               region (lbf)
C      SFSUM                    Summation of all the incremental
                                 shear force
C                               values over the entire pipe (lbf)
C      T                        Local static temperature (R)
C      TEST                     Force balance check (lbf)
C      TW                       Wall shear stress (lbf/ft2)
C      TWBARC                   Average wall shear stress for the
                                 condenser
C                               (lbf/ft2)
C      TO                       Total air temperature (R)
C      UBARC                    Average axial velocity in
                                 condenser, U entering
C                               condenser divided by 2 (ft/sec)
C      U1                       Average velocity at beginning of
                                 DX increment
C                               (ft/sec)
C      U2                       Average velocity at end of DX
                                 increment (ft/sec)
C      W1                       Mass flow rate at the upstream
                                 end of the DX
C                               increment (lbm/sec)
C      W2                       Mass flow rate at the downstream
                                 end of the DX
C                               increment (lbm/sec)
C      WBAR                     Average mass flow rate for DX
                                 increment (lbm/sec)
C      WCK                      Mass flow rate entering condenser
                                 (lbm/sec)
C      XL                       Local axial position (ft)
C      XND                      Non-dimensional axial position,
                                 XL/PL
C      XNDD(1)-XNDD(30) Non-dimensional axial position,
                                 X(I)/PL
C      X(1)-X(30)               Axial location of pressure
                                 measurements (ft)
C
C    *****************************************************
C    * INPUT CONSTANTS AND DECLARE TYPES AND DIMENSIONS *
C    *****************************************************
C
       IMPLICIT REAL*8 (A-H,M,O-Z)
```

```
      REAL*8 X(30),P(30),XNDD(30),PND(30)
      PL = 31.8125/12.0
      X(1) = 0.0
      X(2) = 2.90625/12.0
      X(3) = 4.90625/12.0
      X(4) = 6.90625/12.0
      X(5) = 8.90625/12.0
      X(6) = 10.90625/12.0
      X(7) = 12.90625/12.0
      X(8) = 13.40625/12.0
      X(9) = 13.90625/12.0
      X(10) = 14.40625/12.0
      X(11) = 14.90625/12.0
      X(12) = 15.53125/12.0
      X(13) = 16.28125/12.0
      X(14) = 16.90625/12.0
      X(15) = 17.40625/12.0
      X(16) = 17.90625/12.0
      X(17) = 18.90625/12.0
      X(18) = 19.90625/12.0
      X(19) = 20.90625/12.0
      X(20) = 21.90625/12.0
      X(21) = 22.90625/12.0
      X(22) = 23.90625/12.0
      X(23) = 24.90625/12.0
      X(24) = 25.90625/12.0
      X(25) = 26.90625/12.0
      X(26) = 27.90625/12.0
      X(27) = 28.90625/12.0
      X(28) = 29.90625/12.0
      X(29) = 30.90625/12.0
      X(30) = 31.8125/12.0
      OPEN (UNIT=9,STATUS='NEW',FILE='C:RESULTS.DAT')
      OPEN (UNIT=10,STATUS='OLD',FILE='C:DATA.DAT')
      OPEN (UNIT=11,STATUS='NEW',FILE='C:MACH.DAT')
      OPEN (UNIT=12,STATUS='NEW',FILE='C:REW.DAT')
      OPEN (UNIT=13,STATUS='NEW',FILE='C:REX.DAT')
      OPEN (UNIT=14,STATUS='NEW',FILE='C:P2.DAT')
      OPEN (UNIT=15,STATUS='NEW',FILE='C:TW.DAT')
      OPEN (UNIT=16,STATUS='NEW',FILE='C:F.DAT')
      OPEN (UNIT=17,STATUS='NEW',FILE='C:FBL.DAT')
      OPEN (UNIT=18,STATUS='NEW',FILE='C:RHOV2.DAT')
      OPEN (UNIT=19,STATUS='NEW',FILE='C:SF.DAT')
      OPEN (UNIT=20,STATUS='NEW',FILE='C:DW.DAT')
      OPEN (UNIT=21,STATUS='NEW',FILE='C:PND.DAT')
      OPEN (UNIT=22,STATUS='NEW',FILE='C:FREX.DAT')
      OPEN (UNIT=23,STATUS='NEW',FILE='C:FBLREX.DAT')
      OPEN (UNIT=24,STATUS='NEW',FILE='C:FBT.DAT')
      OPEN (UNIT=25,STATUS='NEW',FILE='C:FBTREX.DAT')
      OPEN (UNIT=26,STATUS='NEW',FILE='C:VERIFY.DAT')
      OPEN (UNIT=27,STATUS='NEW',FILE='C:FEVAP.DAT')
      READ (10,4000) N
```

```
      WRITE (9,5020) N
      READ (10,4010) PATM
      WRITE (9,5030) PATM
      READ (10,4020) TO
      WRITE (9,5040) TO
      READ (10,4010) PSINK
      WRITE (9,5050) PSINK
      DO 10 I = 1,30
      READ (10,4010) P(I)
      P(I) = P(I)*144
      PND(I) = P(I)/P(1)
      XNDD(I) = X(I)/PL
      WRITE (21,5000) XNDD(I),PND(I)
   10 CONTINUE
      WRITE (*,5060)
      READ (*,4030) FUD
      WRITE (*,5061)
      READ (*,4030) MFFB
      WRITE (*,5062)
      READ (*,4030) MFFS
      WRITE (9,5070) FUD, MFFB, MFFS
      PATM = PATM*144
      PSINK = PSINK*144
      DX = 0.005
      A = 3.592472958D8
      WRITE (9,5080)
C
C     **********************************************
C     * INITIALIZE VARIABLES AT PIPE END, X = 0.0 *
C     **********************************************
C
      XL = 0.0
      W1 = 0.0
      M1S = 0.0
      M1 = 0.0
      U1 = 0.0
      P1 = P(1)
      P2 = P1
      T = TO
      R = 53.335
      GC = 32.174
      PEX = PATM
      DWSUM = 0.0
      SFSUM = 0.0
      I = 1
      PZ = P(I)
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
      XO = X(I+1)
      XT = X(I+2)
      XND = 0.0
```

```
      CALL SUBINC
      (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,M1S,
     +DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
      BETA,TW,SF,
     +F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,UBAR,MFFB,
      MFFS)
      WRITE (11,5000) XND, M1
      WRITE (12,5000) XND, REW
      WRITE (13,5000) XND, M1
      WRITE (14,5000) XND, P2
      WRITE (15,5000) XND, M1
      WRITE (16,5000) XND, M1
      WRITE (17,5000) XND, M1
      WRITE (18,5000) XND, RHOV1
      WRITE (19,5000) XND, M1
      WRITE (20,5000) XND, DW
      WRITE (22,5000) XND, M1
      WRITE (23,5000) XND, M1
C
C     NOTE: M1 IS USED IN ABOVE WRITE STATEMENTS TO ZERO
            VARIABLES KNOWN
C           TO BE ZERO AT END OF PIPE.
C
      RHOV1 = RHOV2
      RHO1 = RHO2
      W1 = W2
      P1 = P2
C
C     *************************************
C     ***** BEGIN MARCHING DOWN PIPE *****
C     *************************************
C
      DO 200 J = 1,81
      K = J
C
C     **************************************
C     ******** 0.005 < XL < 0.405 *********
C     ***** 0.001886 < XND < 0.152770 *****
C     **************************************
C
      XL = XL + DX
      CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
      IF (M1 .LT. 0.01) THEN
      CALL SUBINC
      (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
     +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
     +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
     +UBAR,MFFB,MFFS)
      ELSE
      CALL SUBCOMP
      (FUD,A,TO,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
     +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
```

```
     ,REW,
     +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
      ENDIF
      WRITE (11,5000) XND,M2
      WRITE (12,5000) XND,REW
      WRITE (13,5000) XND,REX
      WRITE (14,5000) XND,P2
      WRITE (15,5000) XND,TW
      WRITE (16,5000) XND,F
      WRITE (17,5000) XND,FBL
      WRITE (18,5000) XND,RHOV2
      WRITE (19,5000) XND,SF
      WRITE (20,5000) XND,DW
      WRITE (22,5000) XND,FREX
      WRITE (23,5000) XND,FBLREX
      IF (XND .GT. 0.099 .AND. XND .LT. 0.101) THEN
      WRITE (9,5011) XND,F,REW,REX,BETA,M2,FREX,FBLREX
      ENDIF
C
C     **************************************************
C     * CAPTURE OF VARIABLE QUANTITIES TO BE USED TO *
C     *     VERIFIY PROGRAM BY HAND CALCULATION       *
C     **************************************************
C
      IF (K.EQ.3) THEN
         P1 = P1/144.0
         P2 = P2/144.0
         RHOV1 = RHOV1/144.0
         RHOV2 = RHOV2/144.0
         RHO1 = RHO1/1728.0
         RHO2 = RHO2/1728.0
         RHOBAR = RHOBAR/1728.0
         U1 = U1*12.0
         U2 = U2*12.0
         UBAR = UBAR*12.0
         DPS = -DPS/20736.0
         TW = TW/144.0
         WRITE (26,*) 'K = 3'
         WRITE (26,*) 'P1 = ',P1
         WRITE (26,*) 'P2 = ',P2
         WRITE (26,*) 'RHOV1 = ', RHOV1
         WRITE (26,*) 'RHOV2 = ', RHOV2
         WRITE (26,*) 'W1 = ', W1
         WRITE (26,*) 'W2 = ', W2
         WRITE (26,*) 'DW = ', DW
         WRITE (26,*) 'DWSUM = ', DWSUM
         WRITE (26,*) 'T = ', T
         WRITE (26,*) 'RHO1 = ', RHO1
         WRITE (26,*) 'RHO2 = ', RHO2
         WRITE (26,*) 'RHOBAR = ', RHOBAR
         WRITE (26,*) 'U1 = ', U1
         WRITE (26,*) 'U2 = ', U2
```

```
         WRITE (26,*) 'UBAR = ', UBAR
         WRITE (26,*) 'M1 = ', M1
         WRITE (26,*) 'M1S = ', M1S
         WRITE (26,*) 'M2 = ', M2
         WRITE (26,*) 'M2S = ', M2S
         WRITE (26,*) 'ADPS = ',DPS
         WRITE (26,*) 'F = ', F
         WRITE (26,*) 'FREX = ', FREX
         WRITE (26,*) 'TW = ', TW
         WRITE (26,*) 'SFSUM = ', SFSUM
         WRITE (26,*) 'SF = ', SF
         WRITE (26,*) 'REW = ', REW
         WRITE (26,*) 'REX = ', REX
         P1 = P1*144.0
         P2 = P2*144.0
         RHOV1 = RHOV1*144.0
         RHOV2 = RHOV2*144.0
         RHO1 = RHO1*1728.0
         RHO2 = RHO2*1728.0
         RHOBAR = RHOBAR*1728.0
         U1 = U1/12.0
         U2 = U2/12.0
         UBAR = UBAR/12.0
         DPS = -DPS*20736.0
         TW = TW*144.0
      ENDIF
      IF (K.EQ.4) THEN
         P1 = P1/144.0
         P2 = P2/144.0
         RHOV1 = RHOV1/144.0
         RHOV2 = RHOV2/144.0
         RHO1 = RHO1/1728.0
         RHO2 = RHO2/1728.0
         RHOBAR = RHOBAR/1728.0
         U1 = U1*12.0
         U2 = U2*12.0
         UBAR = UBAR*12.0
         DPS = -DPS/20736.0
         TW = TW/144.0
         WRITE (26,*) ' '
         WRITE (26,*) 'K = 4'
         WRITE (26,*) 'P1 = ',P1
         WRITE (26,*) 'P2 = ',P2
         WRITE (26,*) 'RHOV1 = ', RHOV1
         WRITE (26,*) 'RHOV2 = ', RHOV2
         WRITE (26,*) 'W1 = ', W1
         WRITE (26,*) 'W2 = ', W2
         WRITE (26,*) 'DW = ', DW
         WRITE (26,*) 'DWSUM = ', DWSUM
         WRITE (26,*) 'T = ', T
         WRITE (26,*) 'RHO1 = ', RHO1
         WRITE (26,*) 'RHO2 = ', RHO2
```

```
         WRITE (26,*) 'RHOBAR = ', RHOBAR
         WRITE (26,*) 'U1 = ', U1
         WRITE (26,*) 'U2 = ', U2
         WRITE (26,*) 'UBAR = ', UBAR
         WRITE (26,*) 'M1 = ', M1
         WRITE (26,*) 'M1S = ', M1S
         WRITE (26,*) 'M2 = ', M2
         WRITE (26,*) 'M2S = ', M2S
         WRITE (26,*) 'ADPS = ',DPS
         WRITE (26,*) 'F = ', F
         WRITE (26,*) 'FREX = ', FREX
         WRITE (26,*) 'TW = ', TW
         WRITE (26,*) 'SFSUM = ', SFSUM
         WRITE (26,*) 'SF = ', SF
         WRITE (26,*) 'REW = ', REW
         WRITE (26,*) 'REX = ', REX
         P1 = P1*144.0
         P2 = P2*144.0
         RHOV1 = RHOV1*144.0
         RHOV2 = RHOV2*144.0
         RHO1 = RHO1*1728.0
         RHO2 = RHO2*1728.0
         RHOBAR = RHOBAR*1728.0
         U1 = U1/12.0
         U2 = U2/12.0
         UBAR = UBAR/12.0
         DPS = -DPS*20736.0
         TW = TW*144.0
      ENDIF
C
C     ****************************************
C     ***** END OF VERIFICATION ROUTINE *****
C     ****************************************
C
      RHOV1 = RHOV2
      RHO1 = RHO2
      W1 = W2
      M1S = M2S
      M1 = M2
      U1 = U2
      P1 = P2
200   CONTINUE
      I = 3
      PZ = P(I)
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
      XO = X(I+1)
      XT = X(I+2)
      DO 400 J = 1,67
C
```

```
C     **************************************
C     ******** 0.410 < XL < 0.740 *********
C     ***** 0.154656 < XND < 0.279136 *****
C     **************************************
C
      XL = XL + DX
      CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
      IF (M1 .LT. 0.01) THEN
      CALL SUBINC
      (FUD,A,T0,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
     +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
     +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
     +UBAR,MFFB,MFFS)
      ELSE
      CALL SUBCOMP
      (FUD,A,T0,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
     +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
      ,REW,
     +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
      ENDIF
      WRITE (11,5000) XND,M2
      WRITE (12,5000) XND,REW
      WRITE (13,5000) XND,REX
      WRITE (14,5000) XND,P2
      WRITE (15,5000) XND,TW
      WRITE (16,5000) XND,F
      WRITE (17,5000) XND,FBL
      WRITE (18,5000) XND,RHOV2
      WRITE (19,5000) XND,SF
      WRITE (20,5000) XND,DW
      WRITE (22,5000) XND,FREX
      WRITE (23,5000) XND,FBLREX
      IF (XND .GT. 0.199 .AND. XND .LT. 0.201) THEN
      WRITE (9,5011) XND,F,REW,REX,BETA,M2,FREX,FBLREX
      ENDIF
      RHOV1 = RHOV2
      RHO1 = RHO2
      W1 = W2
      M1S = M2S
      M1 = M2
      U1 = U2
      P1 = P2
  400 CONTINUE
      I = 5
      PZ = P(I)
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
      XO = X(I+1)
      XT = X(I+2)
      DO 600 J = 1,67
C
```

```
C      **************************************
C      ******** 0.745 < XL < 1.075 *********
C      ***** 0.281022 < XND < 0.405501 *****
C      **************************************
C
       XL = XL + DX
       CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
       IF (M1 .LT. 0.01) THEN
       CALL SUBINC
       (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
      +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
      +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
      +UBAR,MFFB,MFFS)
       ELSE
       CALL SUBCOMP
       (FUD,A,TO,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
      +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
       ,REW,
      +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
       ENDIF
       WRITE (11,5000) XND,M2
       WRITE (12,5000) XND,REW
       WRITE (13,5000) XND,REX
       WRITE (14,5000) XND,P2
       WRITE (15,5000) XND,TW
       WRITE (16,5000) XND,F
       WRITE (17,5000) XND,FBL
       WRITE (18,5000) XND,RHOV2
       WRITE (19,5000) XND,SF
       WRITE (20,5000) XND,DW
       WRITE (22,5000) XND,FREX
       WRITE (23,5000) XND,FBLREX
       IF (XND .GT. 0.298 .AND. XND .LT. 0.301) THEN
       WRITE (9,5011) XND,F,REW,REX,BETA,M2,FREX,FBLREX
       ENDIF
       IF (XND .GT. 0.398 .AND. XND .LT. 0.401) THEN
       WRITE (9,5011) XND,F,REW,REX,BETA,M2,FREX,FBLREX
       ENDIF
       RHOV1 = RHOV2
       RHO1 = RHO2
       W1 = W2
       M1S = M2S
       M1 = M2
       U1 = U2
       P1 = P2
   600 CONTINUE
       I = 7
       PZ = P(I)
       PO = P(I+1)
       PT = P(I+2)
       XZ = X(I)
       XO = X(I+1)
```

```
      XT = X(I+2)
      DO 800 J = 1,16
C
C     ****************************************
C     ******** 1.080 < XL < 1.155 *********
C     ***** 0.407387 < XND < 0.435678 *****
C     ****************************************
C
      XL = XL + DX
      CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
      IF (M1 .LT. 0.01) THEN
      CALL SUBINC
      (FUD,A,T0,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
     +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
     +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
     +UBAR,MFFB,MFFS)
      ELSE
      CALL SUBCOMP
      (FUD,A,T0,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
     +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
      ,REW,
     +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
      ENDIF
      WRITE (11,5000) XND,M2
      WRITE (12,5000) XND,REW
      WRITE (13,5000) XND,REX
      WRITE (14,5000) XND,P2
      WRITE (15,5000) XND,TW
      WRITE (16,5000) XND,F
      WRITE (17,5000) XND,FBL
      WRITE (18,5000) XND,RHOV2
      WRITE (19,5000) XND,SF
      WRITE (20,5000) XND,DW
      WRITE (22,5000) XND,FREX
      WRITE (23,5000) XND,FBLREX
      RHOV1 = RHOV2
      RHO1 = RHO2
      W1 = W2
      M1S = M2S
      M1 = M2
      U1 = U2
      P1 = P2
  800 CONTINUE
      I = 9
      PZ = P(I)
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
      XO = X(I+1)
      XT = X(I+2)
      DO 1000 J = 1,17
C
```

```
C       ***************************************
C       ******** 1.160 < XL < 1.240 *********
C       ***** 0.437564 < XND < 0.467741 *****
C       ***************************************
C
        XL = XL + DX
        CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
        IF (M1 .LT. 0.01) THEN
        CALL SUBINC
        (FUD,A,T0,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
       +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
       +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
       +UBAR,MFFB,MFFS)
        ELSE
        CALL SUBCOMP
        (FUD,A,T0,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
       +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
        ,REW,
       +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
        ENDIF
        WRITE (11,5000) XND,M2
        WRITE (12,5000) XND,REW
        WRITE (13,5000) XND,REX
        WRITE (14,5000) XND,P2
        WRITE (15,5000) XND,TW
        WRITE (16,5000) XND,F
        WRITE (17,5000) XND,FBL
        WRITE (18,5000) XND,RHOV2
        WRITE (19,5000) XND,SF
        WRITE (20,5000) XND,DW
        WRITE (22,5000) XND,FREX
        WRITE (23,5000) XND,FBLREX
        RHOV1 = RHOV2
        RHO1 = RHO2
        W1 = W2
        M1S = M2S
        M1 = M2
        U1 = U2
        P1 = P2
  1000  CONTINUE
        I = 11
        PZ = P(I)
        PO = P(I+1)
        PT = P(I+2)
        XZ = X(I)
        XO = X(I+1)
        XT = X(I+2)
        DO 1200 J = 1,23
C
C       ***************************************
C       ******** 1.245 < XL < 1.355 *********
C       ***** 0.469627 < XND < 0.511120 *****
```

```
C      *************************************
C
       XL = XL + DX
       CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
       IF (XND .GT. 0.491 .AND. XND .LT. 0.508) PEX = P2
       IF (XND .GT. 0.508) PEX = PSINK
       IF (M1 .LT. 0.01) THEN
       CALL SUBINC
       (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
      +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
      +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
      +UBAR,MFFB,MFFS)
       ELSE
       CALL SUBCOMP
       (FUD,A,TO,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
      +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
       ,REW,
      +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
       ENDIF
       WRITE (11,5000) XND,M2
       WRITE (12,5000) XND,REW
       WRITE (13,5000) XND,REX
       WRITE (14,5000) XND,P2
       WRITE (15,5000) XND,TW
       WRITE (16,5000) XND,F
       WRITE (17,5000) XND,FBL
       WRITE (18,5000) XND,RHOV2
       WRITE (19,5000) XND,SF
       WRITE (20,5000) XND,DW
       WRITE (22,5000) XND,FREX
       WRITE (23,5000) XND,FBLREX
       IF (XND .GT. 0.508) THEN
       WRITE (24,5000) XND,FBT
       WRITE (25,5000) XND,FBTREX
       ENDIF
       IF (XND .GT. 0.506 .AND. XND .LT. 0.508) THEN
          UBARC = UBAR/2
          REXBRC = REX/2
       ENDIF
       IF (XND .GT. 0.508 .AND. XND .LT. 0.510) THEN
          SFEA = SFSUM
          RHOC = RHO2
       ENDIF
       RHOV1 = RHOV2
       RHO1 = RHO2
       W1 = W2
       M1S = M2S
       M1 = M2
       U1 = U2
       P1 = P2
       IF (XND .GT. 0.489 .AND. XND .LT. 0.491) WCK = DWSUM
 1200  CONTINUE
```

```
      I = 13
      PZ = P(I)
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
      XO = X(I+1)
      XT = X(I+2)
      DO 1400 J = 1,19
C
C     *************************************
C     ******** 1.360 < XL < 1.450 *********
C     ***** 0.513006 < XND < 0.546955 *****
C     *************************************
C
      XL = XL + DX
      CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
      IF (M1 .LT. 0.01) THEN
      CALL SUBINC
      (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
     +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
     +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
     +UBAR,MFFB,MFFS)
      ELSE
      CALL SUBCOMP
      (FUD,A,TO,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
     +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
      ,REW,
     +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
      ENDIF
      WRITE (11,5000) XND,M2
      WRITE (12,5000) XND,REW
      WRITE (13,5000) XND,REX
      WRITE (14,5000) XND,P2
      WRITE (15,5000) XND,TW
      WRITE (16,5000) XND,F
      WRITE (17,5000) XND,FBL
      WRITE (18,5000) XND,RHOV2
      WRITE (19,5000) XND,SF
      WRITE (20,5000) XND,DW
      WRITE (22,5000) XND,FREX
      WRITE (23,5000) XND,FBLREX
      WRITE (24,5000) XND,FBT
      WRITE (25,5000) XND,FBTREX
      RHOV1 = RHOV2
      RHO1 = RHO2
      W1 = W2
      M1S = M2S
      M1 = M2
      U1 = U2
      P1 = P2
 1400 CONTINUE
      I = 15
```

```
      PZ = P(I)
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
      XO = X(I+1)
      XT = X(I+2)
      DO 1600 J = 1,25
C
C     **************************************
C     ******** 1.455 < XL < 1.575 *********
C     ***** 0.548841 < XND < 0.594106 *****
C     **************************************
C
      XL = XL + DX
      CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
      IF (M1 .LT. 0.01) THEN
      CALL SUBINC
      (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
     +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
     +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
     +UBAR,MFFB,MFFS)
      ELSE
      CALL SUBCOMP
      (FUD,A,TO,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
     +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
      ,REW,
     +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
      ENDIF
      WRITE (11,5000) XND,M2
      WRITE (12,5000) XND,REW
      WRITE (13,5000) XND,REX
      WRITE (14,5000) XND,P2
      WRITE (15,5000) XND,TW
      WRITE (16,5000) XND,F
      WRITE (17,5000) XND,FBL
      WRITE (18,5000) XND,RHOV2
      WRITE (19,5000) XND,SF
      WRITE (20,5000) XND,DW
      WRITE (22,5000) XND,FREX
      WRITE (23,5000) XND,FBLREX
      WRITE (24,5000) XND,FBT
      WRITE (25,5000) XND,FBTREX
      RHOV1 = RHOV2
      RHO1 = RHO2
      W1 = W2
      M1S = M2S
      M1 = M2
      U1 = U2
      P1 = P2
 1600 CONTINUE
      I = 17
      PZ = P(I)
```

```
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
      XO = X(I+1)
      XT = X(I+2)
      DO 1800 J = 1,33
C
C     **************************************
C     ******** 1.580 < XL < 1.740 *********
C     ***** 0.595992 < XND < 0.656346 *****
C     **************************************
C
      XL = XL + DX
      CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
      IF (M1 .LT. 0.01) THEN
      CALL SUBINC
      (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
     +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
     +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
     +UBAR,MFFB,MFFS)
      ELSE
      CALL SUBCOMP
      (FUD,A,TO,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
     +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
      ,REW,
     +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
      ENDIF
      WRITE (11,5000) XND,M2
      WRITE (12,5000) XND,REW
      WRITE (13,5000) XND,REX
      WRITE (14,5000) XND,P2
      WRITE (15,5000) XND,TW
      WRITE (16,5000) XND,F
      WRITE (17,5000) XND,FBL
      WRITE (18,5000) XND,RHOV2
      WRITE (19,5000) XND,SF
      WRITE (20,5000) XND,DW
      WRITE (22,5000) XND,FREX
      WRITE (23,5000) XND,FBLREX
      WRITE (24,5000) XND,FBT
      WRITE (25,5000) XND,FBTREX
      IF (XND .GT. 0.599 .AND. XND .LT. 0.601) THEN
      WRITE (9,5010)
      XND,F,REW,REX,BETA,M2,FREX,FBLREX,FBTREX
      ENDIF
      RHOV1 = RHOV2
      RHO1 = RHO2
      W1 = W2
      M1S = M2S
      M1 = M2
      U1 = U2
      P1 = P2
```

```
1800  CONTINUE
      I = 19
      PZ = P(I)
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
      XO = X(I+1)
      XT = X(I+2)
      DO 2000 J = 1,33
C
C     ****************************************
C     ******** 1.745 < XL < 1.905 *********
C     ***** 0.658232 < XND < 0.718585 *****
C     ****************************************
C
      XL = XL + DX
      CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
      IF (M1 .LT. 0.01) THEN
      CALL SUBINC
      (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
     +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
     +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
     +UBAR,MFFB,MFFS)
      ELSE
      CALL SUBCOMP
      (FUD,A,TO,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
     +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
      ,REW,
     +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
      ENDIF
      WRITE (11,5000) XND,M2
      WRITE (12,5000) XND,REW
      WRITE (13,5000) XND,REX
      WRITE (14,5000) XND,P2
      WRITE (15,5000) XND,TW
      WRITE (16,5000) XND,F
      WRITE (17,5000) XND,FBL
      WRITE (18,5000) XND,RHOV2
      WRITE (19,5000) XND,SF
      WRITE (20,5000) XND,DW
      WRITE (22,5000) XND,FREX
      WRITE (23,5000) XND,FBLREX
      WRITE (24,5000) XND,FBT
      WRITE (25,5000) XND,FBTREX
      IF (XND .GT. 0.698 .AND. XND .LT. 0.701) THEN
      WRITE (9,5010)
      XND,F,REW,REX,BETA,M2,FREX,FBLREX,FBTREX
      ENDIF
      RHOV1 = RHOV2
      RHO1 = RHO2
      W1 = W2
      M1S = M2S
```

```
      M1 = M2
      U1 = U2
      P1 = P2
 2000 CONTINUE
      I = 21
      PZ = P(I)
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
      XO = X(I+1)
      XT = X(I+2)
      DO 2200 J = 1,34
C
C     *************************************
C     ******** 1.910 < XL < 2.075 *********
C     ***** 0.720472 < XND < 0.782711 *****
C     *************************************
C
      XL = XL + DX
      CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
      IF (M1 .LT. 0.01) THEN
      CALL SUBINC
      (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
     +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
     +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
     +UBAR,MFFB,MFFS)
      ELSE
      CALL SUBCOMP
      (FUD,A,TO,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
     +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
      ,REW,
     +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
      ENDIF
      WRITE (11,5000) XND,M2
      WRITE (12,5000) XND,REW
      WRITE (13,5000) XND,REX
      WRITE (14,5000) XND,P2
      WRITE (15,5000) XND,TW
      WRITE (16,5000) XND,F
      WRITE (17,5000) XND,FBL
      WRITE (18,5000) XND,RHOV2
      WRITE (19,5000) XND,SF
      WRITE (20,5000) XND,DW
      WRITE (22,5000) XND,FREX
      WRITE (23,5000) XND,FBLREX
      WRITE (24,5000) XND,FBT
      WRITE (25,5000) XND,FBTREX
      RHOV1 = RHOV2
      RHO1 = RHO2
      W1 = W2
      M1S = M2S
      M1 = M2
```

```
      U1 = U2
      P1 = P2
 2200 CONTINUE
      I = 23
      PZ = P(I)
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
      XO = X(I+1)
      XT = X(I+2)
      DO 2400 J = 1,33
C
C     ************************************
C     ******** 2.080 < XL < 2.240 *******
C     ***** 0.784597 < XND < 844951 *****
C     ************************************
C
      XL = XL + DX
      CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
      IF (M1 .LT. 0.01) THEN
      CALL SUBINC
      (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
     +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
     +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
     +UBAR,MFFB,MFFS)
      ESE
      CALL SUBCOMP
      (FUD,A,TO,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
     +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
      ,REW,
     +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
      ENDIF
      WRITE (11,5000) XND,M2
      WRITE (12,5000) XND,REW
      WRITE (13,5000) XND,REX
      WRITE (14,5000) XND,P2
      WRITE (15,5000) XND,TW
      WRITE (16,5000) XND,F
      WRITE (17,5000) XND,FBL
      WRITE (18,5000) XND,RHOV2
      WRITE (19,5000) XND,SF
      WRITE (20,5000) XND,DW
      WRITE (22,5000) XND,FREX
      WRITE (23,5000) XND,FBLREX
      WRITE (24,5000) XND,FBT
      WRITE (25,5000) XND,FBTREX
      IF (XND .GT. 0.799 .AND. XND .LT. 0.801) THEN
      WRITE (9,5010)
      XND,F,REW,REX,BETA,M2,FREX,FBLREX,FBTREX
      ENDIF
      RHOV1 = RHOV2
      RHO1 = RHO2
```

```
      W1 = W2
      M1S = M2S
      M1 = M2
      U1 = U2
      P1 = P2
2400  CONTINUE
      I = 25
      PZ = P(I)
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
     XO = X(I+1)
     XT = X(I+2)
     DO 2600 J = 1,33
C
C    **************************************
C    ******** 2.245 < XL < 2.405 *********
C    ***** 0.846837 < XND < 0.907191 *****
C    **************************************
C
     XL = XL + DX
     CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
     IF (M1 .LT. 0.01) THEN
     CALL SUBINC
     (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
    +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,REW,
    +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
    +UBAR,MFFB,MFFS)
     ELSE
     CALL SUBCOMP
     (FUD,A,TO,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
    +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
     ,REW,
    +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
     ENDIF
     WRITE (11,5000) XND,M2
     WRITE (12,5000) XND,REW
     WRITE (13,5000) XND,REX
     WRITE (14,5000) XND,P2
     WRITE (15,5000) XND,TW
     WRITE (16,5000) XND,F
     WRITE (17,5000) XND,FBL
     WRITE (18,5000) XND,RHOV2
     WRITE (19,5000) XND,SF
     WRITE (20,5000) XND,DW
     WRITE (22,5000) XND,FREX
     WRITE (23,5000) XND,FBLREX
     WRITE (24,5000) XND,FBT
     WRITE (25,5000) XND,FBTREX
     IF (XND .GT. 0.899 .AND. XND .LT. 0.901) THEN
     WRITE (9,5010)
     XND,F,REW,REX,BETA,M2,FREX,FBLREX,FBTREX
```

```
      ENDIF
       RHOV1 = RHOV2
       RHO1 = RHO2
       W1 = W2
       M1S = M2S
       M1 = M2
       U1 = U2
       P1 = P2
 2600  CONTINUE
        I = 27
        PZ = P(I)
        PO = P(I+1)
        PT = P(I+2)
        XZ = X(I)
        XO = X(I+1)
        XT = X(I+2)
        DO 2800 J = 1,34
C
C       *************************************
C       ******** 2.410 < XL < 2.575 *********
C       ***** 0.909077 < XND < 0.971316 *****
C       *************************************
C
        XL = XL + DX
        CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
        IF (M1 .LT. 0.01) THEN
        CALL SUBINC
        (FUD,A,TO,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
       +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX
        ,REW,
       +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
       +UBAR,MFFB,MFFS)
        ELSE
        CALL SUBCOMP
        (FUD,A,TO,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
       +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,
        REX,REW,
       +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
        ENDIF
        WRITE (11,5000) XND,M2
        WRITE (12,5000) XND,REW
        WRITE (13,5000) XND,REX
        WRITE (14,5000) XND,P2
        WRITE (15,5000) XND,TW
        WRITE (16,5000) XND,F
        WRITE (17,5000) XND,FBL
        WRITE (18,5000) XND,RHOV2
        WRITE (19,5000) XND,SF
        WRITE (20,5000) XND,DW
        WRITE (22,5000) XND,FREX
        WRITE (23,5000) XND,FBLREX
        WRITE (24,5000) XND,FBT
```

```
      WRITE (25,5000) XND,FBTREX
      RHOV1 = RHOV2
      RHO1 = RHO2
      W1 = W2
      M1S = M2S
      M1 = M2
      U1 = U2
      P1 = P2
 2800 CONTINUE
      I = 28
      PZ = P(I)
      PO = P(I+1)
      PT = P(I+2)
      XZ = X(I)
      XO = X(I+1)
      XT = X(I+2)
      DO 3000 J = 1,15
C
C     *************************************
C     ******** 2.580 < XL < 2.650 *********
C     ***** 0.973202 < XND < 0.999607 *****
C     *************************************
C
      XL = XL + DX
      CALL SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
      IF (M1 .LT. 0.01) THEN
      CALL SUBINC
       (FUD,A,T0,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
     +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,
      REW,
     +BETA,TW,SF,F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,
     +UBAR,MFFB,MFFS)
      ELSE
      CALL SUBCOMP
       (FUD,A,T0,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
     +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,
      REX,REW,
     +BETA,TW,SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
      ENDIF
      WRITE (11,5000) XND,M2
      WRITE (12,5000) XND,REW
      WRITE (13,5000) XND,REX
      WRITE (14,5000) XND,P2
      WRITE (15,5000) XND,TW
      WRITE (16,5000) XND,F
      WRITE (17,5000) XND,FBL
      WRITE (18,5000) XND,RHOV2
      WRITE (19,5000) XND,SF
      WRITE (20,5000) XND,DW
      WRITE (22,5000) XND,FREX
      WRITE (23,5000) XND,FBLREX
      WRITE (24,5000) XND,FBT
```

```
      WRITE (25,5000) XND,FBTREX
      RHOV1 = RHOV2
      RHO1 = RHO2
      W1 = W2
      M1S = M2S
      M1 = M2
      U1 = U2
      P1 = P2
3000  CONTINUE
      PI = 3.1415926536D0
      D = 0.5/12.0
      CL = (31.8125 - 16.15625)/12.0
      AC = PI*D**2/4.0
      PF = (P(1) - P(30))*AC
      TEST = PF - SFSUM
      PEF = DABS(100.0*TEST/PF)
      PEM = DABS(100.0*DWSUM/WCK)
      WRITE (9,5090) PF,TEST,PEF,WCK,DWSUM,PEM
      SFC = PF - SFEA
      TWBARC = SFC/(PI*D*CL)
      FBARC = 2.0*GC*TWBARC/(RHOC*UBARC**2)
      FCREXC = FBARC*REXBRC
      WRITE (9,5100) FBARC
      WRITE (9,5110) FCREXC
C
C     *************************
C     ***** READ FORMAT'S *****
C     *************************
C
4000  FORMAT (I1)
4010  FORMAT (F15.12)
4020  FORMAT (F6.2)
4030  FORMAT (F5.3)
C
C     **************************
C     ***** WRITE FORMAT'S *****
C     **************************
C
5000  FORMAT (1X,F20.13,5X,F20.13)
5010  FORMAT
      (2X,F4.3,2X,F8.5,2X,F9.4,2X,F9.3,3X,F6.4,2X,F8.6,
      3X,F9.5,
     +5X,F8.5,3X,F8.5)
5011  FORMAT
      (2X,F4.3,2X,F8.5,2X,F9.4,2X,F9.3,3X,F6.4,2X,F8.6,
      3X,F9.5,
     +5X,F8.5)
5020  FORMAT (45X,'TEST RUN # ',I1,////)
5030  FORMAT (15X,'Patm        =  ',F7.4,1X,'psia',/)
5040  FORMAT (15X,'T0          = ',F6.2,3X,'R',/)
5050  FORMAT (15X,'Psink       =  ',F7.4,1X,'psia',//)
5060  FORMAT (3X,'ENTER THE POROSITY FLUX CORRECTION
```

```
     FACTOR, X.XXX')
5061 FORMAT (3X,'ENTER THE BLOWING MOMENTUM FLUX
     FACTOR, X.XXX')
5062 FORMAT (3X,'ENTER THE SUCTION MOMENTUM FLUX
     FACTOR, X.XXX')
5070 FORMAT (15X,'Porosity',/,15x,'Flux Factor =
     ',2X,F5.3,//,15X,
    +'Blowing Momentum',/,15X,'Flux Factor =
     ',2x,F5.3,//,15X,
    +'Suction Momentum',/,15X,'Flux Factor =
     ',2X,F5.3,///)
5080 FORMAT
     (21X,'RADIAL',6X,'AXIAL',37X,'FB(REX)',4X,'FB(REX)'
     ,/,
    +3X,'X/L',2X,'FRICTION',3X,'REYNOLDS',3X,'REYNOLDS',
     5X,'BETA',
    +6X,'MACH',6X,'F(REX)',6X,'F. DEV.',4X,'F.
     DEV.',/,10X,'FACTOR',
    +5X,'NUMBER',5X,'NUMBER',13X,'NUMBER',18X,'LAMINAR'
     ,2X,
    +'TURBULENT',/)
5090 FORMAT (///,15X,'Pressure Force',5X,'=
     ',F18.14,1X,'lbf',
    +//,15X,'Force Balance',6X,'=
     ',F18.14,1X,'lbf',//,15X,'% Error',
    +12X,'= ',F8.4,////,15X,'Mass Flow Rate',/,15X,
    +'Entering Condenser =
     ',F18.14,1X,'lbm/sec',//,15X,'Mass Balance',
    +7X,'= ',F18.14,1X,'lbm/sec',//,15X,'%
     Error',12X,'= ',F8.4)
5100 FORMAT (//,15X,'Average
     Condenser',/,15X,'Friction Factor',4X,
    +'= ',F18.14)
5110 FORMAT (//,15X,'Average Condenser',/,15X,'f(Rex)
     product',5X,
    +'= ',F18.14)
C
     CLOSE (9)
     CLOSE (10)
     CLOSE (11)
     CLOSE (12)
     CLOSE (13)
     CLOSE (14)
     CLOSE (15)
     CLOSE (16)
     CLOSE (17)
     CLOSE (18)
     CLOSE (19)
     CLOSE (20)
     CLOSE (21)
     CLOSE (22)
     CLOSE (23)
```

```
      CLOSE (24)
      CLOSE (25)
C
C     ********************************
C     ****** END OF MAIN PROGRAM *****
C     ********************************
C
      END
```

Name	Type	Offset	P	Class
A	REAL*8	1034		
AC	REAL*8	1458		
BETA	REAL*8	1298		
CL	REAL*8	1450		
D	REAL*8	1442		
DABS				INTRINSIC
DPS	REAL*8	1202		
DW	REAL*8	1274		
DWSUM	REAL*8	1130		
DX	REAL*8	1026		
F	REAL*8	1322		
FBARC	REAL*8	1514		
FBL	REAL*8	1330		
FBLREX	REAL*8	1354		
FBT	REAL*8	1338		
FBTREX	REAL*8	1362		
FCREXC	REAL*8	1522		
FREX	REAL*8	1346		
FUD	REAL*8	1002		
GC	REAL*8	1114		
I	INTEGER*4	998		
J	INTEGER*4	1386		
K	INTEGER*4	1390		
M1	REAL*8	1066		
M1S	REAL*8	1058		
M2	REAL*8	1266		
M2S	REAL*8	1258		
MFFB	REAL*8	1010		
MFFS	REAL*8	1018		
N	INTEGER*4	970		
P	REAL*8	482		
P1	REAL*8	1082		
P2	REAL*8	1090		
PATM	REAL*8	974		
PEF	REAL*8	1482		
PEM	REAL*8	1490		
PEX	REAL*8	1122		
PF	REAL*8	1466		
PI	REAL*8	1434		
PL	REAL*8	962		
PND	REAL*8	722		

```
PO       REAL*8          1154
PSINK    REAL*8           990
PT       REAL*8          1162
PZ       REAL*8          1146
R        REAL*8          1106
REW      REAL*8          1290
REX      REAL*8          1282
REXBRC   REAL*8          1402
RHO1     REAL*8          1210
RHO2     REAL*8          1226
RHOBAR   REAL*8          1370
RHOC     REAL*8          1418
RHOV1    REAL*8          1218
RHOV2    REAL*8          1234
SF       REAL*8          1314
SFC      REAL*8          1498
SFEA     REAL*8          1410
SFSUM    REAL*8          1138
T        REAL*8          1098
TO       REAL*8           982
TEST     REAL*8          1474
TW       REAL*8          1306
TWBARC   REAL*8          1506
U1       REAL*8          1074
U2       REAL*8          1242
UBAR     REAL*8          1378
UBARC    REAL*8          1394
W1       REAL*8          1050
W2       REAL*8          1250
WCK      REAL*8          1426
X        REAL*8             2
XL       REAL*8          1042
XND      REAL*8          1194
XNDD     REAL*8           242
XO       REAL*8          1178
XT       REAL*8          1186
XZ       REAL*8          1170
```

```
C
C    ****************************************************
C    INTERPOLATION SUBROUTINE TO DETERMINE LOCAL PRESSURE
C    ****************************************************
C
        SUBROUTINE SUBPRES (PZ,PO,PT,XZ,XO,XT,XL,XND,P2)
C
C       ** GIVEN THREE PRESSURES, PZ, PO, & PT, AT THREE
        LOCATIONS,
C       XZ, XO, & XT, THIS SUBROUTINE INTERPOLATES
        TO FIND THE
C       PRESSURE, P2, WITH THE REQUIREMENT XO < XL
        < XT.  XL IS
```

```
C        REFERRED TO AS "STATION 2" **
C
         IMPLICIT REAL*8 (A-H,O-Z)
         PL = 31.8125/12.0
         CC1 = PZ/((XZ - XO)*(XZ - XT))
         CC2 = PO/((XO - XZ)*(XO - XT))
         CC3 = PT/((XT - XZ)*(XT - XO))
         P2 = CC1*(XL - XO)*(XL - XT) + CC2*(XL - XZ)*(XL
         - XT) + CC3*(XL
        +- XZ)*(XL -XO)
         XND = XL/PL
         RETURN
         END
```

Name	Type	Offset	P	Class
CC1	REAL*8	3076		
CC2	REAL*8	3084		
CC3	REAL*8	3092		
P2	REAL*8	32	*	
PL	REAL*8	3068		
PO	REAL*8	4	*	
PT	REAL*8	8	*	
PZ	REAL*8	0	*	
XL	REAL*8	24	*	
XND	REAL*8	28	*	
XO	REAL*8	16	*	
XT	REAL*8	20	*	
XZ	REAL*8	12	*	

```
C
C        *********************************************
C        ***** INCOMPRESSIBLE MODEL SUBROUTINE *****
C        *********************************************
C
         SUBROUTINE SUBINC
         (FUD,A,T0,PEX,XND,P2,DPS,RHO1,RHOV1,U1,W1,M1,
        +M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,REX,
         REW,BETA,T
         W,SF,

        +F,FBL,FBT,P1,FREX,FBLREX,FBTREX,RHOBAR,UBAR,MFFB,
         MFFS)
C
C    ** THIS SUBROUTINE CALCULATES FLOW PROPETIES AT
C        STATION 2 BASED ON AN INCOMPRESSIBLE MODEL **
C
         IMPLICIT REAL*8 (A-H,M,O-Z)
         PI = 3.1415926536D0
         D = 0.5/12.0
         DX = 0.005
```

```
      AP = PI*D*DX
      AC = PI*D**2/4.0
      GC = 32.174
      R = 53.335
      GAM = 1.4
      GAM1 = 0.2
      PL = 31.8125/12.0
      CL = (31.8125/2.0 - 0.25)/12.0
      DPS = P2**2 - PEX**2
      ADPS = DABS(DPS)
      RHOV2 = FUD*GC*ADPS/A
      IF (XND .LT. 0.5) RHOV2 = -RHOV2
      RHOVAV = (RHOV1 + RHOV2)/2.0
      DW = -RHOVAV*AP
      DWSUM = DWSUM + DW
      W2 = W1 + DW
      WBAR = (W1 + W2)/2.0
      RHO2 = P2/(R*T)
      RHOBAR = (RHO1 + RHO2)/2.0
      C2 = GC*GAM*P2/RHO2
      U2 = RHO1*U1/RHO2 + DW/(RHO2*AC)
      UBAR = (U1 + U2)/2.0
      M2S = U2**2/C2
      MSBAR = (M1S + M2S)/2.0
      M2 = DSQRT(M2S)
      CON1 = 1 + GAM1*MSBAR
      T = T0/CON1
      RMU = 2.27E-08*DSQRT(T**3)/(T + 198.6)
      REX = 4.0*WBAR/(PI*D*RMU*GC)
      REW = RHOVAV*D/(RMU*GC)
      BETA = DABS(REW/REX)
      MFF1 = MFFB
      MFF2 = MFFB
      IF (XND .GT. 0.508) MFF2 = MFFS
      IF (XND .GT. 0.510) MFF1 = MFFS
      DMOM = W2*U2*MFF2/GC - W1*U1*MFF1/GC
      TW = ((P1 - P2)*AC - DMOM)/AP
      SF = TW*AP
      SFSUM = SFSUM + SF
      F = 2.0*GC*TW/(RHOBAR*UBAR**2)
      AREX = DABS(REX)
      FBL = 16.0/REX*(1.2337 -
      0.2337*DEXP(0.0363*REW))*DEXP(1.2*MSBAR)
      FSTAR = 0.079/AREX**0.25
      FBT = FSTAR*(1.0 + 17.5*AREX**0.25*BETA)
      FREX = F*REX
      FBLREX = FBL*REX
      FBTREX = FBT*REX
      IF (XND .LT. 0.491) THEN
      WRITE (27,6000) F,FBL
      ENDIF
 6000 FORMAT (1X,F13.9,2X,F13.9)
```

```
      RETURN
      END
```

Name	Type	Offset	P	Class
A	REAL*8	4	*	
AC	REAL*8	3132		
ADPS	REAL*8	3188		
AP	REAL*8	3124		
AREX	REAL*8	3268		
BETA	REAL*8	100	*	
C2	REAL*8	3212		
CL	REAL*8	3180		
CON1	REAL*8	3228		
D	REAL*8	3108		
DABS				INTRINSIC
DEXP				INTRINSIC
DMOM	REAL*8	3260		
DPS	REAL*8	24	*	
DSQRT				INTRINSIC
DW	REAL*8	88	*	
DWSUM	REAL*8	52	*	
DX	REAL*8	3116		
F	REAL*8	112	*	
FBL	REAL*8	116	*	
FBLREX	REAL*8	132	*	
FBT	REAL*8	120	*	
FBTREX	REAL*8	136	*	
FREX	REAL*8	128	*	
FSTAR	REAL*8	3276		
FUD	REAL*8	0	*	
GAM	REAL*8	3156		
GAM1	REAL*8	3164		
GC	REAL*8	3140		
M1	REAL*8	44	*	
M1S	REAL*8	48	*	
M2	REAL*8	84	*	
M2S	REAL*8	80	*	
MFF1	REAL*8	3244		
MFF2	REAL*8	3252		
MFFB	REAL*8	148	*	
MFFS	REAL*8	152	*	
MSBAR	REAL*8	3220		
P1	REAL*8	124	*	
P2	REAL*8	20	*	
PEX	REAL*8	12	*	
PI	REAL*8	3100		
PL	REAL*8	3172		
R	REAL*8	3148		
REW	REAL*8	96	*	
REX	REAL*8	92	*	
RHO1	REAL*8	28	*	

```
RHO2   REAL*8        64 *
RHOBAR REAL*8       140 *
RHOV1  REAL*8        32 *
RHOV2  REAL*8        68 *
RHOVAV REAL*8      3196
RMU    REAL*8      3236
SF     REAL*8       108 *
SFSUM  REAL*8        60 *
T      REAL*8        56 *
T0     REAL*8         8 *
TW     REAL*8       104 *
U1     REAL*8        36 *
U2     REAL*8        72 *
UBAR   REAL*8       144 *
W1     REAL*8        40 *
W2     REAL*8        76 *
WBAR   REAL*8      3204
XND    REAL*8        16 *
```

```
C
C         ****************************************
C         ***** COMPRESSIBLE MODEL SUBROUTINE *****
C         ****************************************
C
          SUBROUTINE SUBCOMP
          (FUD,A,T0,PEX,XND,P2,DPS,P1,RHO1,RHOV1,U1,W1,
         +M1,M1S,DWSUM,T,SFSUM,RHO2,RHOV2,U2,W2,M2S,M2,DW,
          REX,REW,BET,A,TW,
         +SF,F,FBL,FBT,FREX,FBLREX,FBTREX,RHOBAR,UBAR)
C
C      ** THIS SUBROUTINE CALCULATES FLOW PROPETIES AT
C         STATION 2 BASED ON A COMPRESSIBLE MODEL **
C
          IMPLICIT REAL*8 (A-H,M,O-Z)
          PI = 3.1415926536D0
          D = 0.5/12.0
          DX = 0.005
          AP = PI*D*DX
          AC = PI*D**2/4.0
          GC = 32.174
          R = 53.335
          GAM = 1.4
          GAM1 = 0.2
          PL = 31.8125/12.0
          CL = (31.8125/2.0 - 0.25)/12.0
          DPS = P2**2 - PEX**2
          ADPS = DABS(DPS)
          RHOV2 = FUD*GC*ADPS/A
          IF (XND .LT. 0.5) RHOV2 = -RHOV2
          RHOVAV = (RHOV1 + RHOV2)/2.0
          DW = -RHOVAV*AP
```

```
      DWSUM = DWSUM + DW
      W2 = W1 + DW
      WBAR = (W1 + W2)/2.0
      CM = M1S*(1.0 +
      GAM1*M1S)*((W2/W1)**2)/((P2/P1)**2)
      M2S = (-1.0 + DSQRT(1.0 +
      4.0*GAM1*CM))/(2.0*GAM1)
      MSBAR = (M1S + M2S)/2.0
      M2 = DSQRT(M2S)
      CON1 = 1 + GAM1*MSBAR
      T = T0/CON1
      RHO2 = P2/(R*T)
      RHOBAR = (RHO1 + RHO2)/2.0
      C2 = GC*GAM*P2/RHO2
      U2 = M2*DSQRT(C2)
      UBAR = (U1 + U2)/2.0
      RMU = 2.27E-08*DSQRT(T**3)/(T + 198.6)
      REX = 4.0*WBAR/(PI*D*RMU*GC)
      REW = RHOVAV*D/(RMU*GC)
      BETA = DABS(REW/REX)
      CFP = (1.0 + GAM*MSBAR)/(GAM*MSBAR)
      F = 0.5*(D/DX)*(DLOG(M1S/M2S) - CFP*DLOG(P2/P1))
      TW = 0.5*F*RHOBAR*UBAR**2/GC
      SF = TW*AP
      SFSUM = SFSUM + SF
      AREX = DABS(REX)
      FBL = 16.0/REX*(1.2337 -
      0.2337*DEXP(0.0363*REW))*DEXP(1.2*MSBAR)
      FSTAR = 0.079/AREX**0.25
      FBT = FSTAR*(1.0 + 17.5*AREX**0.25*BETA)
      FREX = F*REX
      FBLREX = FBL*REX
      FBTREX = FBT*REX
      IF (XND .LT. 0.491) THEN
      WRITE (27,6000) F,FBL
      ENDIF
 6000 FORMAT (1X,F13.9,2X,F13.9)
      RETURN
      END
```

Name	Type	Offset	P	Class
A	REAL*8	4	*	
AC	REAL*8	3336		
ADPS	REAL*8	3392		
AP	REAL*8	3328		
AREX	REAL*8	3464		
BETA	REAL*8	104	*	
C2	REAL*8	3440		
CFP	REAL*8	3456		
CL	REAL*8	3384		
CM	REAL*8	3416		

CON1	REAL*8	3432		
D	REAL*8	3312		
DABS				INTRINSIC
DEXP				INTRINSIC
DLOG				INTRINSIC
DPS	REAL*8	24	*	
DSQRT				INTRINSIC
DW	REAL*8	92	*	
DWSUM	REAL*8	56	*	
DX	REAL*8	3320		
F	REAL*8	116	*	
FBL	REAL*8	120	*	
FBLREX	REAL*8	132	*	
FBT	REAL*8	124	*	
FBTREX	REAL*8	136	*	
FREX	REAL*8	128	*	
FSTAR	REAL*8	3472		
FUD	REAL*8	0	*	
GAM	REAL*8	3360		
GAM1	REAL*8	3368		
GC	REAL*8	3344		
M1	REAL*8	48	*	
M1S	REAL*8	52	*	
M2	REAL*8	88	*	
M2S	REAL*8	84	*	
MSBAR	REAL*8	3424		
P1	REAL*8	28	*	
P2	REAL*8	20	*	
PEX	REAL*8	12	*	
PI	REAL*8	3304		
PL	REAL*8	3376		
R	REAL*8	3352		
REW	REAL*8	100	*	
REX	REAL*8	96	*	
RHO1	REAL*8	32	*	
RHO2	REAL*8	68	*	
RHOBAR	REAL*8	140	*	
RHOV1	REAL*8	36	*	
RHOV2	REAL*8	72	*	
RHOVAV	REAL*8	3400		
RMU	REAL*8	3448		
SF	REAL*8	112	*	
SFSUM	REAL*8	64	*	
T	REAL*8	60	*	
T0	REAL*8	8	*	
TW	REAL*8	108	*	
U1	REAL*8	40	*	
U2	REAL*8	76	*	
UBAR	REAL*8	144	*	
W1	REAL*8	44	*	
W2	REAL*8	80	*	
WBAR	REAL*8	3408		

```
XND     REAL*8            16 *


Name    Type              Size    Class

ONED                              PROGRAM
SUBCOM                            SUBROUTINE
SUBINC                            SUBROUTINE
SUBPRE                            SUBROUTINE


 Pass One     No Errors Detected
             1369 Source Lines
```

Appendix C

TEST RUN # 1

Patm = 14.2827 psia

T0 = 526.50 R

Psink = 14.2444 psia

Porosity
Flux Factor = 1.000

Blowing Momentum
Flux Factor = 1.290

Suction Momentum
Flux Factor = 1.470

X/L	FRICTION FACTOR	RADIAL REYNOLDS NUMBER	AXIAL REYNOLDS NUMBER	BETA	MACH NUMBER	F(REX)
.100	.18663	-3.4595	87.995	.0393	.000312	16.42282
.200	.09210	-3.4621	176.035	.0197	.000625	16.21332
.300	.06123	-3.4665	264.163	.0131	.000938	16.17488
.400	.04737	-3.4726	352.423	.0099	.001251	16.69325
.600	.03083	3.4723	354.203	.0098	.001252	10.91849
.700	.05958	3.4734	265.850	.0131	.000938	15.84048
.800	.08847	3.4740	177.478	.0196	.000624	15.70187
.900	.12791	3.4745	89.092	.0390	.000310	11.39598

Pressure Force = .00001883160918 lbf

Force Balance = .00000000005909 lbf

% Error = .0003

Mass Flow Rate
Entering Condenser = .00017256225293 lbm/sec

Mass Balance = -.00000005382849 lbm/sec

% Error = .0312

Average Condenser
Friction Factor = .06447082216418

Average Condenser
f(Rex) product = 13.99607226000200

TEST RUN # 2

Patm = 14.2484 psia

TO = 526.00 R

Psink = 14.2281 psia

Porosity
Flux Factor = 1.000

Blowing Momentum
Flux Factor = 1.305

Suction Momentum
Flux Factor = 1.370

X/L	FRICTION FACTOR	RADIAL REYNOLDS NUMBER	AXIAL REYNOLDS NUMBER	BETA	MACH NUMBER	F(REX)
.100	.34820	-1.8347	46.669	.0393	.000166	16.24985
.200	.17400	-1.8357	93.355	.0197	.000332	16.24329
.300	.11622	-1.8375	140.076	.0131	.000498	16.27910
.400	.08698	-1.8399	186.850	.0098	.000664	16.25176
.600	.08404	1.8414	187.725	.0098	.000664	15.77694
.700	.11145	1.8409	140.887	.0131	.000497	15.70123
.800	.16664	1.8405	94.061	.0196	.000331	15.67422
.900	.33160	1.8403	47.242	.0390	.000165	15.66552

Pressure Force = .00001122276190 lbf

Force Balance = .00000000000089 lbf

% Error = .0000

Mass Flow Rate
Entering Condenser = .00009140706303 lbm/sec

Mass Balance = -.00000000598701 lbm/sec

% Error = .0065

Average Condenser
Friction Factor = .13496525522116

Average Condenser
f(Rex) product = 15.53163701557668

TEST RUN # 3

Patm = 14.3022 psia

T0 = 526.00 R

Psink = 14.2308 psia

Porosity
Flux Factor = 1.000

Blowing Momentum
Flux Factor = 1.270

Suction Momentum
Flux Factor = 1.600

X/L	FRICTION FACTOR	RADIAL REYNOLDS NUMBER	AXIAL REYNOLDS NUMBER	BETA	MACH NUMBER	F(REX)
.100	.10239	-6.4532	164.129	.0393	.000582	16.80494
.200	.05118	-6.4602	328.378	.0197	.001164	16.80719
.300	.03387	-6.4720	492.866	.0131	.001747	16.69245
.400	.02542	-6.4885	657.713	.0099	.002332	16.72037
.600	.02416	6.4716	661.560	.0098	.002334	15.98275
.700	.02319	6.4815	496.794	.0130	.001750	11.52303
.800	.04039	6.4884	331.809	.0196	.001165	13.40302
.900	.06137	6.4937	166.669	.0390	.000580	10.22789

Pressure Force = .00002995839503 lbf

Force Balance = .00000000004151 lbf

% Error = .0001

Mass Flow Rate
Entering Condenser = .00032190622080 lbm/sec

Mass Balance = -.00000002620157 lbm/sec

% Error = .0081

Average Condenser
Friction Factor = .03506096928445

Average Condenser
f(Rex) product = 14.20926769146199

TEST RUN # 4

Patm = 14.2729 psia

TO = 526.00 R

Psink = 14.1330 psia

Porosity
Flux Factor = 1.000

Blowing Momentum
Flux Factor = 1.245

Suction Momentum
Flux Factor = 1.600

X/L	FRICTION FACTOR	RADIAL REYNOLDS NUMBER	AXIAL REYNOLDS NUMBER	BETA	MACH NUMBER	F(REX)
.100	.05462	-12.5627	319.471	.0393	.001138	17.45062
.200	.02702	-12.5848	639.317	.0197	.002277	17.27199
.300	.01815	-12.6219	959.915	.0131	.003418	17.41907
.400	.01360	-12.6740	1281.648	.0099	.004564	17.43204
.600	.01261	12.5920	1290.864	.0098	.004575	16.27655
.700	.01401	12.6353	969.950	.0130	.003432	13.58974
.800	.02095	12.6676	648.078	.0195	.002286	13.57851
.900	.12140	12.6756	325.702	.0389	.001138	39.54022

Pressure Force = .00005293412287 lbf

Force Balance = .00000000069008 lbf

% Error = .0013

Mass Flow Rate
Entering Condenser = .00062766683506 lbm/sec

Mass Balance = .00000004480944 lbm/sec

% Error = .0071

Average Condenser
Friction Factor = .02606307347730

Average Condenser
f(Rex) product = 20.59576260070104

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19. This thesis examines the combined effects of pressure gradients and blowing and suction on frictional forces in a heat pipe with relatively low radial Reynolds numbers. A porous tube is used to simulate the heat pipe and a vacuum pump is used to generate the air flow. By measuring the static pressure variation along the pipe wall and using a one-dimensional, incompressible, numerical model, the frictional forces are obtained and compared to laminar fully-developed theoretical values. Four flow rate cases with radial Reynolds numbers of 1.8, 3.5, 6.5, and 12.6 were studied. In this range, the flow in the evaporator was fully-developed. In the condenser, however, the fully-developed solution consistently under predicted the average condenser friction coefficient. Deviation from the fully-developed solution increased as the flow rate increased.

Keywords

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